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Attenuation of hydrogen sulfide from landfill gas study and exploration of construction and demolition debris characteristics and production

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ATTENUATION OF HYDROGEN SULFIDE FROM LANDFILL GAS STUDY AND EXPLORATION OF CONSTRUCTION AND DEMOLITION DEBRIS CHARACTERISTICS AND PRODUCTION

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ABSTRACT

ATTENUATION OF HYDROGEN SULFIDE FROM LANDFILL GAS STUDY AND EXPLORATION OF CONSTRUCTION AND DEMOLITION DEBRIS CHARACTERISTICS AND PRODUCTION

By

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Hydrogen sulfide (H_2S) has become recognized as a problematic gas emitted from landfills. Sulfate, which can produce H_2S in a landfill, is in drywall in construction and demolition (C&D) debris and sometimes products or recycling. This research consisted of examining alternative treatment of H_2S gas at landfills, input/output of sulfur at landfills and generation/prevention of H_2S in the landfill setting using C&D. In this research, four ashes were tested with landfill gas to investigate H_2S attenuation, the highest attenuation reached was 73.8mg of H_2S per gram of ash. In addition, these exhausted ashes, as well as sulfur cake were placed in a landfill simulated environment to investigate if they could regenerate H_2S and from the results, appears that sulfur cake is most likely to regenerate H_2S. The experiment involving the prevention of H_2S showed that it is unclear whether these materials have the ability to inhibit the production of H_2S.

CHAPTER 1

INTRODUCTION

Hydrogen sulfide (H_2S) production from construction and demolition (C&D) landfills as well as from municipal solid waste (MSW) landfills has become increasingly recognized as an environmental problem in recent decades. Hydrogen sulfide is produced from sulfate containing materials in a landfill, which can include gypsum drywall in C&D debris and sewerage sludge. C&D debris is generated from the construction, demolition or repair of buildings roads and bridges. The composition of C&D debris is primarily wood, asphalt, masonry and drywall. Other materials present are a function of what kind of structure is producing the debris (ICF Inc, 1995). The drywall component has been recognized as the major source of H_2S as it contains gypsum ($CaSO_4$). Under anaerobic conditions present at a landfill, the gypsum dissociates into calcium and sulfate when introduced to water, which is also present. The sulfate is then reduced to H_2S by sulfate reducing bacteria (SRB) that use the sulfate as an electron acceptor (Plaza et al, 2007). More details of this process will be discussed later in this thesis.

Regulations have been promulgated at both the state and federal level for C&D and MSW landfills. Appropriate regulations for construction, groundwater and air quality monitoring, as well as operation are in place to ensure that potential contaminants do not cause harm to humans or the environment (ICF Inc, 1995). For the purposes of this research, emissions of H_2S are the primary chemical concern.

The health effects of H_2S are recognized by the EPA and various international organizations. Although H_2S in the gaseous form is easily detectable at concentrations as low as 0.011mg/m^3, at concentrations greater than 700mg/m^3 it can cause eye damage, dizziness, olfactory paralysis, respiratory distress and even death. Incidents of death have been recorded in confined spaces and the effects of hydrogen sulfide can be seen in only one or two inhalations of the gas (US EPA, 2003).

Other than health issues, H_2S emissions from landfill gas is undesirable because it has an offensive odor, causes corrosion and produces sulfur oxides (SO_x) if/when it is flared. H_2S has a distinct "rotten egg" odor that can be detected at concentrations as low as 0.5 ppm (US EPA, 2003). Because H_2S in the aqueous form is corrosive, it has the potential to damage metal pipes and structures involved with landfill gas management. Moreover, if the landfill gas is used for energy production at landfills, the concentration needs to be reduced because of its corrosive nature. If H_2S does get flared, it oxidizes to sulfur dioxide SO_2 and enters the atmosphere in this form. According to Cooper and Alley (1994), this negatively affects plants resulting in them to lose chlorophyll and SO_2 also may produce a sulfuric deposit, commonly known as acid rain, which also has harmful environmental effects.

Therefore, the source reduction of materials that tend to produce H_2S has become increasingly incorporated in practice and policy. There are facilities operating that recycle C&D debris, but having a byproduct of C&D fines is inevitable. As mentioned, this debris will likely contain gypsum (unless drywall is removed upfront of processing), which can produce H_2S in an environment such as a landfill. So, in order to find an appropriate disposal for the C&D fines as well as to find an inexpensive alternative daily

cover (ADC), landfill operators were inclined to use the C&D fines. Increasingly with further studies showing the aforementioned problems associated with disposing of the C&D fines in this manner, states in the northeast part of the United States, as well as in other areas of the country, have banned C&D fines in landfills. Consequently, further management and disposal methods of C&D fines need to be pursued.

Industrial materials, such as ash, have been were examined in this research to determine if they can attenuate H_2S in landfill gas (Melendez, 2008). It has been hypothesized and a preliminary investigation completed that different industrial/recycled materials have the potential to attenuate H_2S (Melendez, 2008). In addition, activated carbons such as bituminous coal, wood, coconut shells, and peat have been tested as sorbents of hydrogen sulfide gas (Bandosz, 2002). Despite not having consensus on the mechanism for the sorption of H_2S, it is believed that adsorption may play the largest role in attenuation. Physical, or Van der Waal's, forces cause the $H_2S_{(aq)}$ to dissociate on the water surface of the carbon adsorbent. The H_2S dissociates to HS^- and elemental sulfur (Bandosz, 2002).

This research also involved the analysis of sulfate content in C&D debris fines produced from different facilities. The relationship between the sulfate content from different facilities as well the H_2S produced from these facilities will be presented and discussed.

Another aspect of the research was to evaluate if the disposal of spent material used for H_2S adsorption regenerates H_2S. It is possible that the H_2S attenuated may chemically transform to a different sulfur chemical during the adsorption process. However, there may be potential for the material containing the adsorbed sulfur

compounds back into a reducing environment (such as a landfill) may degrade the sulfur compound back in H_2S. Therefore, an experiment was conducted to simulate a landfill environment where the exhausted media (having attenuated H_2S) would be introduced to reducing conditions.

A final experiment conducted for this research investigated whether various materials could be mixed with the fines (e.g., used as ADC) determine if H_2S production can be hindered or prevented if disposed of in a landfill environment. As will be discussed further in this paper, the methods for the prevention of H_2S production include pH alteration, oxidation and adsorption.

This paper is divided into five chapters. Chapter 1 contains the introduction. Chapter 2 consists of a literature review. Chapter 3 contains a description of materials and methods while Chapter 4 presents the results and discussion. Finally, Chapter 5 contains conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Hydrogen Sulfide Characterization

Hydrogen sulfide, (H_2S), in the gaseous form is colorless and has a "rotten egg" odor. It is also known as stink damp, sour gas, sewer gas and hydrogen sulfuric acid (US EPA, 2003). Hydrogen sulfide is composed of two hydrogen atoms and one sulfur atom and has a structural formula of H-S-H. It also has a molecular weight of 34.08. H_2S is soluble in water between 0.5mg/L and 1.0mg/L and soluble in other liquids as well. The solvents in which H_2S is soluble are alcohol, glycerol, ether, kerosene, crude oil and carbon disulfide. In addition, the Henry's constant for this gas is 468 atm/mol (ASTDR, 2006). A H_2S concentration in the air between 4% and 45% is found to be flammable and can also be explosive (ASTDR, 2006). In the aqueous form, of the three sulfur species, S^{2-}, HS^- and H_2S, H_2S is the typical sulfur species at a pH lower than approximately 7. At a pH greater than 7, the dominant sulfur species would be HS^-, and at a pH greater than 12.92, the dominant sulfur species would be S^{2-}. H_2S can be corrosive as well, when it dissolves into water and reacts with oxygen. It forms sulfuric acid (H_2SO_4) with oxygen, which has the tendency to attack metals (Benjamin, 2002). In addition, H_2S is 0.2 times heavier than air (ATSDR, 2006). Therefore, $H_2S_{(g)}$ will tend to migrate to ground level in the presence of air.

This gas is found in nature from volcanic activities, hot springs, petroleum and hot springs. In addition, H_2S is produced from the breakdown of organic matter as well as from many different industrial activities. These industrial activities include petroleum refineries, coke ovens, tanneries, food processing facilities and paper mills (ASTDR, 2006). H_2S can also be measured in biological samples including human breath, animal tissue (although it does not tend to bioaccumulate), blood and saliva (ASTDR, 2006).

2.2 The Sulfur Cycle

Sulfur, in all its forms, is the tenth most abundant element in the earth's crust and accounts for about 1% of the dry weight of bacterial cells. In general, sulfur is cycled between sulfate (SO_4^{2-}) with a +6 oxidation state, and sulfide (S^{2-}) with a -2 oxidation state. Sulfur is required in certain vitamins, hormones and coenzymes. Sulfur is also is necessary for cells to synthesize amino acids cysteine and methione (Maier et al., 2000).

Sulfur enters the environment through volcanic releases primarily in the form of sulfur dioxide (SO_2) and COS as seen in Figure 2.1. In addition, sulfur can also enter the atmosphere in the form of H_2S. These chemicals often become dissolved in the ocean and aquifers in the form of metal sulfides and metal sulfates, respectively. A majority of the sulfides and sulfates are converted into rock while much of the remainder dissolves in the ocean or enters a soil environment. The sulfur that enters the ocean and soil is used as nutrients for microbes that exist in those environments. A third place to where the sulfur from volcanic gases travels is the atmosphere. The sulfur compounds tend to stay in the atmosphere for short periods of time (days). The sulfur compounds are also either precipitated out or fall out, if they are particulates. In the atmosphere, sulfur gases that

do not precipitate and that cycled back are present. The sulfur gases in the atmosphere are oxidized to a soluble sulfate form. The majority of this sulfur in the atmosphere is SO_2, with half being anthropogenic. Another portion consists of H_2S and is mainly from biological activity (Dobrovolsky, 1994).

Of the reservoirs where sulfur is present (atmosphere, ocean and land), the earth's crust, contains the largest amount of sulfur (1.8×10^{16} metric tons). The sulfur deposits exist mainly in the form of inert sulfur compounds including pyrite, FeS_2, and gypsum, $CaSO_4$ as well as sulfur used as fossil fuels (Dobrovolsky, 1994). In addition, soil will absorb sulfur, mainly in the form of elemental sulfur. Because H_2S is soluble in water and oil, H_2S has the tendency to enter groundwater or surface water and travel long distances (ASTDR, 2006).

As previously mentioned, a large amount of sulfur is present in the ocean, on the order of about 1.2×10^{15} metric tons. As one can see from Figure 2.1, the sulfur present in the ocean is mostly inorganic ions, primarily sulfate. The sulfur is slowly cycled there and is more rapidly cycled in the biomass that exists there (Dobrovolsky, 1994). The half life of H_2S in marine environments in biomass is anywhere from one to several hours. This is due to marine organisms degrading H_2S to elemental sulfur. In addition, in these environments, H_2S has the ability to be adsorbed onto clay and organic matter (ASTDR, 2006).

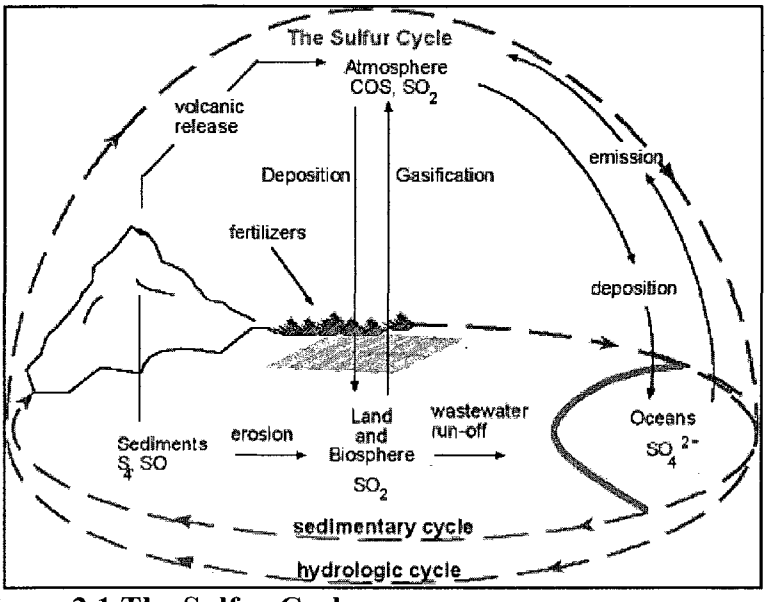


Figure 2.1 The Sulfur Cycle
(http://telstar.ote.cmu.edu/environ/m3/s4/cycleSulfur.shtml)

2.3 The Microbial Sulfur Cycle

Sulfur often is transformed into different electron states and compounds by microbial activity. Sulfur can either be oxidized in the presence of oxygen, or reduced under anaerobic conditions. If the environment is anaerobic, then reduction will occur and SO_4^{2-} can be reduced all the way to H_2S, if other environmental factors are favorable. The opposite can occur in an aerobic environment, as microbes can oxidize H_2S to SO_4^{2-} (Fenchel et al., 1998).

In sulfur oxidation, H_2S first has to be oxidized to elemental sulfur by a specialized group of microbes. Typically, H_2S is toxic to most animals and plants, except ruminant animals. Oxidation can occur in either an aerobic or anaerobic environment. In aerobic environments, Thiobacillus and other bacteria will oxidize H_2S to elemental sulfur and sulfate (Fig. 2.2) (Postgate, 1984). These bacteria are chemoautotrophs as they get their energy from oxidizing molecules, and they exist at the interface of H_2S and

O_2. They can be found in environments like swampy soil, mud, and acidic mine waters, (Germida, 1998).

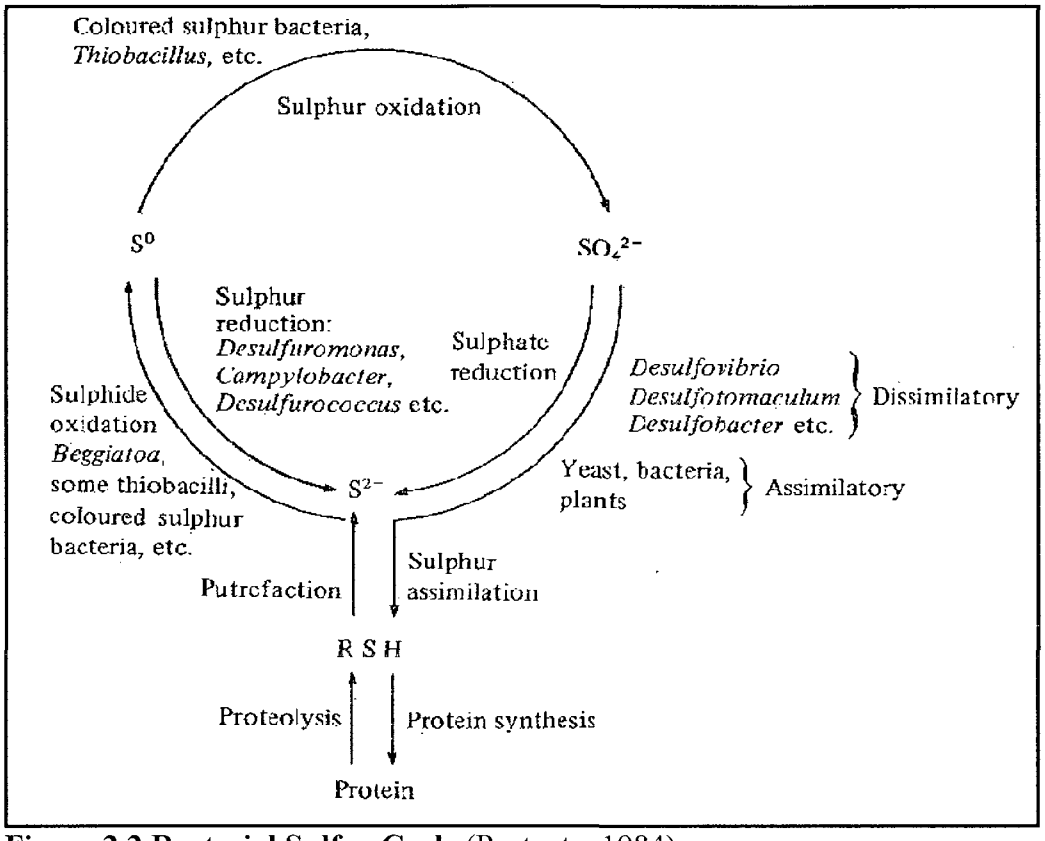


Figure 2.2 Bacterial Sulfur Cycle (Postgate, 1984)

Beggiatoa, a chemoautotroph, will oxidize H_2S to elemental sulfur at the interface of O_2 and H_2S. This type of bacteria is also microaerophilic in that it thrives in environments with low oxygen tension, such as marshes. When in this environment, the microbes will convert oxygen and H_2S to elemental sulfur and water as seen in Eq. 2.1. The environments in which these organisms live contain black deposits due to the presence of elemental sulfur (Maier et al., 2000).

$$H_2S + 0.5\ O_2 \rightarrow S^o + H_2O \qquad \text{(Eq. 2.1)}$$

Thiobacillus, well as other chemoautotrophs, will reduce sulfur to sulfate, as seen in Eq. 2.2. This organism produces acid and thus thrives in environment with a pH as low as 2 (Maier et al., 2000). However, sulfur oxidation can take place where the pH is as high as 9.0 and tends to decrease as different oxidizing steps occur (Postgate, 1984). Sulfur reducing bacteria and iron-oxidizing bacteria are responsible for producing acid-mine drainage as well as recovering precious metals from low grade ore in a process called metallurgy (Maier et al., 2000).

$$S^0 + 1.5\ O_2 + H_2O \rightarrow H_2SO_4 \qquad \text{(Eq. 2.2)}$$

Sulfur can be biologically used in two different ways: assimilatory and dissimilatory. In assimilatory sulfur reduction, inorganic sulfate is reduced to protein, amino acids and other biological products. This can be done either aerobically or anaerobically (Postgate, 1984). Sulfate is used instead of sulfide because sulfide tends to be toxic to cells because it reacts with metals and forms metal-sulfide particles. These particles destroy cytochrome activity. Sulfide is more common for microorganisms and plants to incorporate into amino acids and other molecules which contain sulfur (Maier et al., 2000).

The process in which assimilatory sulfate is reduced is done in several steps, which can be seen in Figure 2.3. The sulfate enters the cell and with adenosine tri-phosphate (ATP) produces adenosine phosphosulfate (APS) and pyrophosphate (Ppi). The ATP and APS form 3-phosphoadenosine-5-phosphate (PAPS). After two more steps, H_2S is produced and with the addition the amino acid serine, another amino acid, cysteine is produced. The sulfur can further be released from the organic molecules in a process called sulfur mineralization. In this process, the cysteine produced in

assimilatory sulfate reduction can be converted to H_2S with the aid of the enzyme serine sulfhydrylase (Maier et al., 2000).

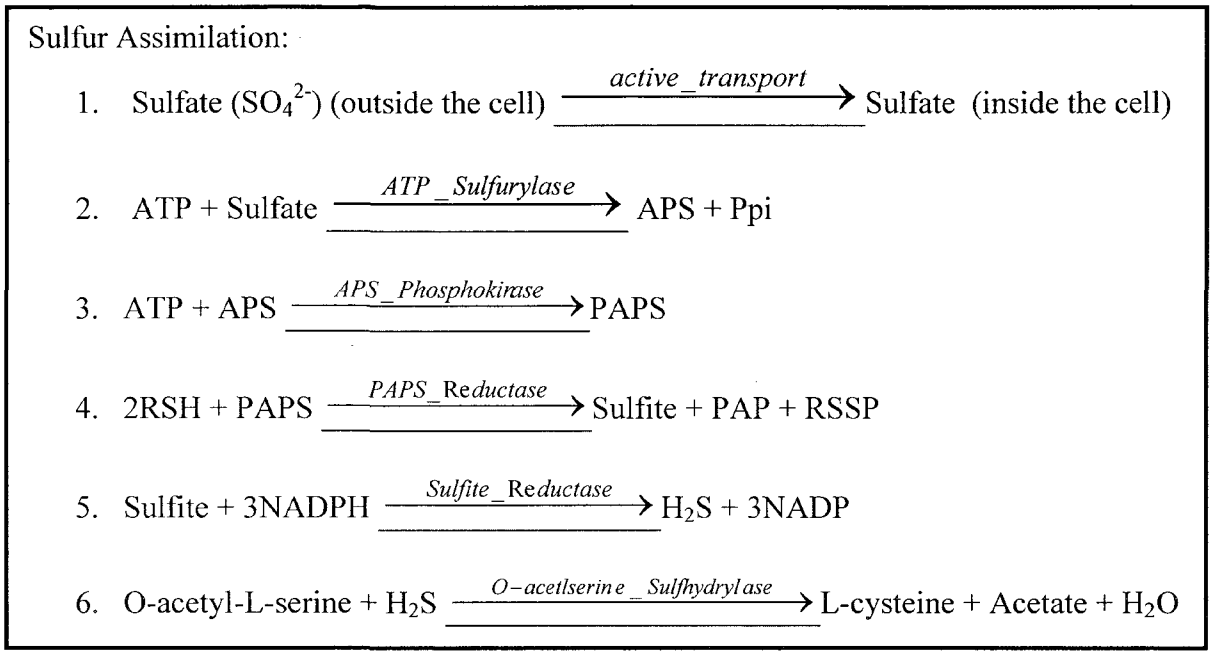


Figure 2.3 Sulfur Assimilation (Adapted from Maier et al., 2000)

In dissimilatory sulfate reduction, inorganic sulfur is the terminal electron acceptor, and the process occurs under anaerobic conditions. In this process, most of the reduced sulfur released is in the form of H_2S and a smaller percentage is released in the form of sulfide (Postgate, 1984). Some of the sulfate is directly reduced to sulfite (SO_3^{2-}). This sulfite is converted to sulfide by enzymes in the bacteria, although most of it is excreted (Tang et al., 2009). However, an even smaller amount of the reduced sulfur is assimilated into the body of the organism for various biological activities. The process of sulfur dissimilation is analogous to the release of O_2 from humans when they inhale CO_2 (Postgate, 1984).

The bacteria responsible for this type of reduction are referred to as sulfate reducing bacteria (SRB). As one can see from Eq. 2.3, SRB use H_2 as an electron donor

to reduce sulfate to sulfur (S^{2-}), and ultimately H_2S (Maier et al., 2000). SRB can also use organic compounds to reduce sulfate. These compounds include lactate, pyruvate, acetate as well as other carbon sources. They metabolize these carbon sources to produce water, CO_2 and other products (Postgate, 1984). Furthermore, in environments such as landfills, SRB will compete with methanogens for H_2. Methanogens and SRB as well as fermenters are part of a consortium that completely mineralizes organic compounds to produce CO_2 and CH_4 (Maier et al., 2000).

$$4H_2 + SO_4^{2-} \rightarrow S^{2-} + 4H_2O \qquad \text{(Eq. 2.3)}$$

2.4 Health Effects of Hydrogen Sulfide

As previously mentioned, the EPA and other international organizations recognize the negative health effects caused by exposure to H_2S. People are most often exposed to H_2S when working with petroleum, natural gas, sewer gas, soil or chemical reactions involving H_2S (U.S. EPA, 2003). There are several ways in which the H_2S can enter the human body and cause harm; they include inhalation, contact with the skin or eyes, and ingestion. This gas can also be detected at concentrations as low as 0.5 parts per billion (ppb). In addition, if H_2S is breathed in for 2 to 15 minutes at concentrations of 100 parts per million (ppm) then the olfactory glands of the nose become desensitized and the smell is no longer noticeable (ASTDR, 2006). This also occurs at a concentration of an excess of 140 mg/m3, as 1ppm H_2S in air is about 1.4mg H_2S in m^3 of air and can be seen in Table 2.1 (Selene and Chou, 2003).

Acute exposure to H_2S is primarily a concern in terms of inhalation and the gas coming in contact with the eyes. Contact with the skin can cause frostbite only if the H_2S is in liquid form, which occurs below a temperature of -60°C. Ingestion also is not of concern for the same reason. However, short term exposure to H_2S is of concern if inhaled because inhaling H_2S can cause headaches, dizziness, nausea, a sore throat, and delayed lung edema. In addition, exposure to high concentrations (greater than 500ppm or about 700mg/m^3) can lead to unconsciousness and death, which can also be seen in Table 2.1 (ASTDR, 2006).

Table 2.1 Exposure Threshold Responses on Humans*

Exposure (mg/m^3)	**Effect / observation**
0.011	Odor threshold
2.8	Bronchial constriction in asthmatic individuals
5	Increased eye complaints
7 or 14	Increased blood lactate concentration, decreased skeletal muscle citrate synthase activity, decreased oxygen uptake
5–29	Eye irritation
28	Fatigue, loss of appetite, headache, irritability, poor memory, dizziness
>140	Olfactory paralysis
>560	Respiratory distress
≥700	Death

*From Selene and Chou, 2003

The Agency for Toxic Substances and Disease Registry has noted the long-term effects of H_2S exposure as well. For example, there are cases where chronic headaches, short attention span, memory loss and poor motor function persists in individuals who have been exposed to H_2S (ASTDR, 2006). Also, as previously mentioned, the EPA has studied both the carcinogenic and noncarcinogenic effects of H_2S. The noncarcinogenic

effects have been analyzed to see if a reference dose for chronic exposure (RfD) can be determined. The RfD is a threshold where the substance can be consumed without negative noncarcinogenic effects. The last agreed upon RfD for H_2S from the EPA was 3 x 10^{-3} mg of substance per kg of body weight per day based on gastrointestinal disturbance. This value was from a study in 1964 where pigs were used as test subjects. Because the RfD value was found to be irreproducible, the RfD was deemed inappropriate and the EPA is working on updating this value (ASTDR, 2006).

The EPA also has tried to find a reference concentration for chronic inhalation exposure (RfC) for H_2S. The RfC is similar to the RfD as the RfC is a limit of daily exposure of a substance where toxic effects such as cellular necrosis will occur in humans. The RfC for H_2S is 2 x 10^{-3} mg H_2S/m^3 of air. This was based on a study on nasal lesions on rats done in 2000. This had to be extrapolated to humans and therefore an uncertainty factor of 300 has been applied (U.S. EPA, 2003).

The EPA also has not been able to submit a carcinogenic assessment for lifetime exposure to H_2S. Data that the EPA has found was deemed to be insufficient to determine whether H_2S has any carcinogenic effects when the EPA last updated its data on H_2S (U.S. EPA, 2003). In addition, other agencies such as the Department of Health and Human Services as well as the International Agency for Research on Cancer have also not been able to find sufficient data to determine whether or not H_2S is carcinogenic (ASTDR, 2006).

2.5 Environmental Effects of Hydrogen Sulfide

There are also environmental concerns when H_2S is emitted in the atmosphere. The problem arises from the fact that sulfur oxide (SO_2) is produced when H_2S is emitted

into the atmosphere and when H_2S is burned at a site such as a landfill. SO_2 is known to cause loss of chlorophyll in plants as well as produce an acidic deposition known as acid rain (Cooper and Alley, 1994). The SO_2 reacts with water in the air to produce sulfurous acid (H_2SO_3) as seen in Eq. 2.4 (Maier et al., 2000).

$$SO_{2(g)} + H_2O \rightarrow H_2SO_3 \qquad \text{(Eq. 2.4)}$$

A low pH can be extremely harmful to aquatic environments and stone buildings and structures. The pH of acid rain from sulfuric acid can reach as low as 3.5 (Maier et al., 2000). There are even lakes that have become so acidic from acid rain that fish can no longer live there. At a pH of 5 or lower, many different fish eggs cannot hatch. A low pH can also cause the soils of the lake to leach out harmful metals and toxins such as aluminum which can harm nearby plant life (U.S. EPA, 2008a).

Bacterial production of acidic metabolites has also shown to cause concrete corrosion. Sulfur oxidizing bacteria tend to produce metabolites, such as organic acids, through fermentation processes. This type of activity often occurs in concrete sewer pipes. In the liquid environment in these pipes, the sewage provides an anaerobic environment with sufficient organic matter such that the SRB can produce sulfide. Ensuing this, the sulfide will volatize to the form of H_2S upon entering the liquid-water interface. The H_2S oxidizes to sulfuric acid in the presence of sulfur oxidizing bacteria that colonize along the concrete walls in the aerobic area in the head space of the pipe. The sulfuric acid reacts with the calcium hydroxide [$Ca(OH)_2$] binder in the concrete to produce calcium sulfate ($CaSO_4$) and water as seen in Eq. 2.5 (Maier et al., 2000).

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O \qquad \text{(Eq. 2.5)}$$

Because of this reaction, the pH of the moisture in the corroded concrete can reach as low 2. In addition, it has been found that the bacteria responsible for this type of corrosion, *T. thiooxidans*, exist in populations of 100,000 cells per gram of concrete. Because of these bacteria, corrosion of concrete can occur at rates of 4.3 to 4.7 mm annually (Figure 2.4). Corrosion at this rate can reduce the life expectancy of sewer pipes to about 20 years (Maier et al., 2000). However, it was noted that by the addition of fly ash in concrete, the sewer pipe can last between 90 and 160 years (Zhang et al., 2008).

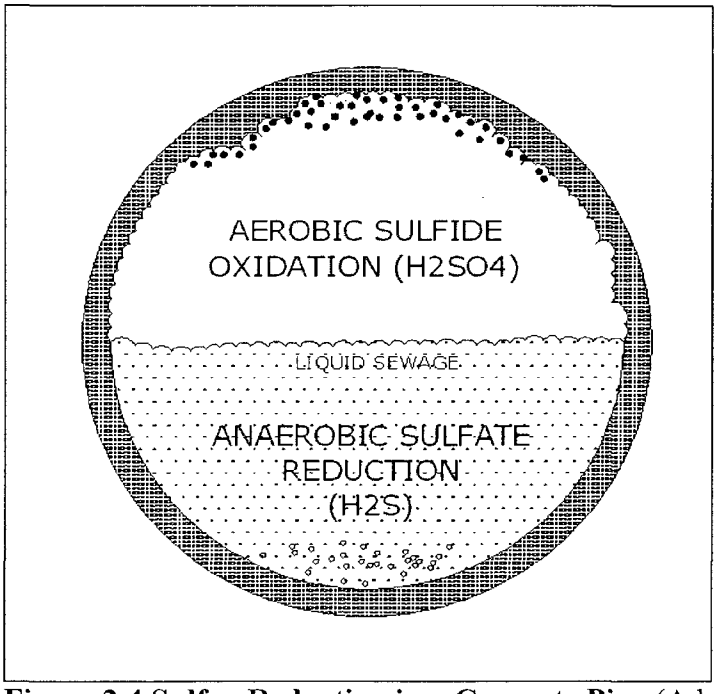


Figure 2.4 Sulfur Reduction in a Concrete Pipe (Adapted from Maier et al, 2000)

2.6 C&D Characterization

Construction and demolition (C&D) debris degradation at landfills is deemed to be a responsible for much of the H_2S produced at landfills (Lee et al., 2006). C&D debris is produced as a result of the construction, renovation or demolition of residential and nonresidential structures. Typical sources of C&D debris include building construction, building construction and demolition, demolition of physical facilities including concrete structures, excavation/leveling, heavy construction, human made disasters (terrorism/sabotage), natural disaster, road construction and site clearing. These are considered nonhazardous waste and often landfilled with municipal solid waste (MSW) along with municipal sludge, combustion ash, automobile bodies, etc (Tchobanoglous and Kreith, 2002).

A large percentage of C&D is considered rubbish (concrete, asphalt, bricks and dirt), between 20 and 30 percent is wood and wood related products and the other 20 to 30 percent is miscellaneous materials such as metals, glass, tar based materials, etc . These values can vary based on geographic location, type of construction project and different construction practices (Tchobanoglous and Kreith, 2002). A similar classification of the different sources is seen in Table 2.2 below. This was produced by the EPA and essentially distinguishes what the miscellaneous materials are (U.S. EPA, 2007)

Table 2.2 Typical C&D Sources*

Source	Percent
Concrete and mixed rubble	40-50
Wood	20-30
Drywall	5-15
Asphalt roofing	1-10
Metals	1-5
Bricks	1-5
Plastics	1-5

*(U.S. EPA, 2007)

In addition, the EPA estimates that 136 million tons of building related C&D are produced annually as of 1996. This can be normalized such that on average, each person produces about 2.8 pounds per day (U.S. EPA, 2007). It also has been determined that 48% of the debris is from building demolition, 44% come from renovations and new construction is responsible for 9% of the total. It is also estimated that total amount of noncommercial C&D debris can be normalized to about 2.0 pounds per person per day. Assuming a population of about 300 million, this would indicate that the U.S. produces over 100 million tons annually (Tchobanoglous and Kreith, 2002).

Often, the C&D debris is sent to processing facilities in order to dispose of the C&D debris in a more environmental friendly and more inexpensive way than simply placing the C&D waste directly into a MSW landfill or a C&D landfill. The processing facilities split the stream of waste into different categories so that much of the C&D debris can be beneficially used or recycled. Wood, like other materials mentioned in Table 2.2, is often separated from the remainder of the waste. A byproduct of these facilities is a screened material, termed "C&D fines" in the Northeast, containing mostly soil and pieces of building material, including drywall. These fines are often used in MSW landfills as alternative daily cover to abate vectors, fire, odor and scavenging.

Additionally, these fines can be used for final cover or shaping and grading purposes. Concerns about these fines causing health and odor issues have led some states to regulate the use and disposal of C&D fines (Musson et al., 2007).

Apart from the aforementioned H_2S health concerns of C&D debris, another one of the health concerns with C&D debris is the presence of heavy metals. There are three health concerns of heavy metals with C&D fines, according to Townsend et al. (2004). These concerns include the contaminants in the debris, hazardous materials (lead-based paint and treated wood – although much of this is to be removed before processing) and the potential for leaching out contaminants (Townsend et al., 2004).

However, the EPA does not regulate C&D debris as a hazardous waste or solid waste under the Resource Conservation and Recovery Act – it is defined and regulated at the state level. Although if the C&D is deposited in a MSW landfill or in a landfill where waste is accepted from conditionally exempt small quantity generators(CESQG), then the landfill is to meet the requirements promulgated under RCRA subtitle D (Tchobanoglous and Kreith, 2002). Because nonmunicipal landfills were exempt, the Sierra Club sued the EPA (ICF Incorporated, 1995). Therefore, as of July 1, 1996, nonmunicipal landfills that receive CESQC waste were also required to follow technical guidelines. These guidelines include local restrictions, groundwater monitoring, as well as corrective action standards (Federal Register, 1996).

2.7 Microbiology of C&D and Landfills

As previously mentioned, one component of C&D debris is drywall. Drywall is composed of about 90% gypsum (calcium sulfate) and about 10% paper on the back and

front (Musson et al., 2008). The gypsum is relatively soluble at about 1300mg/L (Lee et al., 2006). The presence of gypsum can pose a problem at landfills. Anywhere from 1.5-9.1% of the mass of C&D debris is sulfate (Jang and Townsend, 2001). A high presence of sulfate can be an obstruction to the production of methane (CH_4) at landfills. CH_4 is often used as a form of energy at landfills. Currently, 420 landfills are using CH_4 in the landfill gas to produce energy (U.S. EPA, 2008b).

The sulfate in landfill has the potential to divert available electrons to sulfate reduction, as opposed to methanogenesis (Palmisano and Barlaz, 1996). This was further reaffirmed as a study was conducted using multiple-linear regression to see which environmental factors have an impact on methane production. Of the ten factors, moisture content, sulfate, nitrogen and cellulose to lignin ratio were deemed to be significant. This study suggests that sulfate reducing bacteria (SRB) may outcompete the methanogenic bacteria to electron donors like hydrogen and acetate, while other electron donors such as methanol remain unaffected by the sulfate (Gurijala et al., 1997).

However, this theory has been disproved by a study conducted on wastes containing calcium sulfate (Fairweather et al., 1998). SRB require an anaerobic environment, and a relatively neutral pH. In addition, it is suggested that a sulfate electron acceptor and organic carbon are necessary (Postgate, 1984). It appears that the presence of sulfate does not limit production of methane in refuse with plentiful organic carbon. This was shown through the expected organic carbon, cellulose, to be converted to methane does not change even with sulfate added. According to this study, between 2.9 and 7.0 times more cellulose was biodegraded by methanogens compared to SRB (Fairweather et al., 1998). Although H_2S production from sulfate may occur in small

pockets of the landfill, the production may be attributed to the waste containing higher concentrations of sulfate, preferential paths for the gas to travel (if data is taken by gas samples), moisture content and the composition of other waste and soil (Lee et al., 2006).

The introduction of a large concentration of sulfate indicates the ability for SRB to thrive in a landfill; it, however, does not imply that the dynamics of the microbial process of a landfill will necessarily be significantly altered. The substrates will still be introduced and through microbial degradation will occur in such a way that methane and byproducts will be the final result. While many different components are introduced into a landfill (Figure 2.5), the two principle decomposable components of a landfill are cellulose and hemicellulose, and to a lesser degree lignin. These decomposable materials are present in substances in such as paper, food scraps, yard trimmings and wood. The production of methane and pertinent to this paper, H_2S, in landfills is said to be done in a take place in a bioreactor and experts have characterized this process in four phases (Palmisano and Barlaz, 1996).

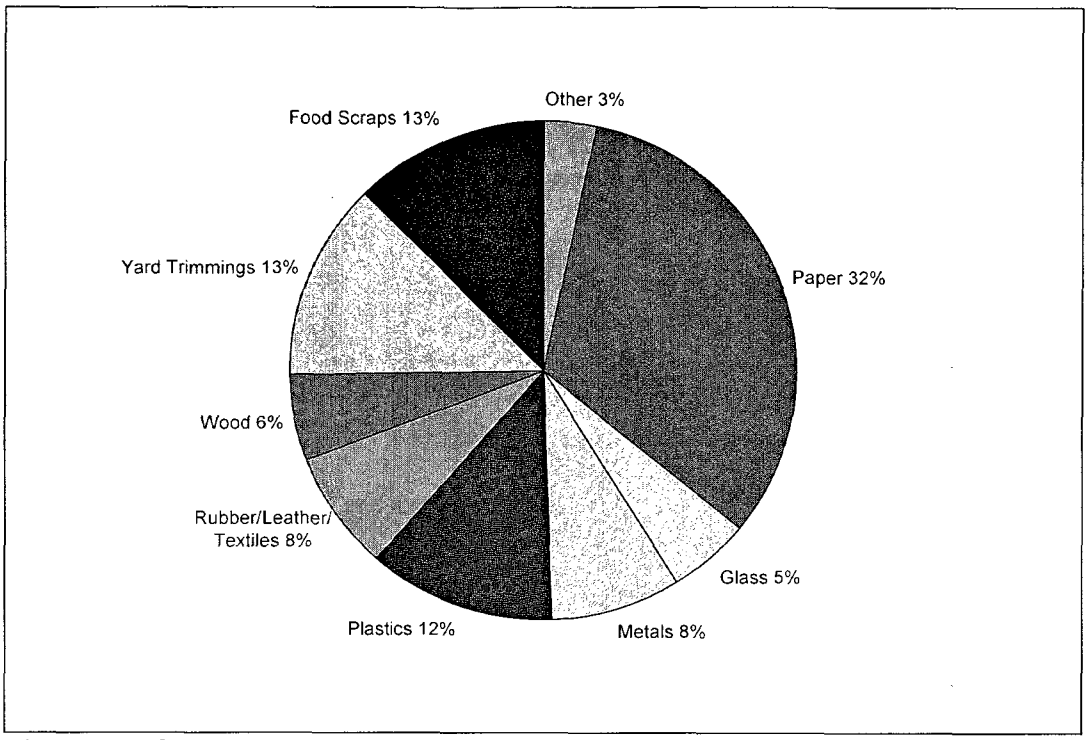


Figure 2.5 Composition of Municipal Solid Sanitary Landfill (Adapted from U.S. EPA, 2007)

When waste initially is put in a landfill, oxygen is present in void spaces and in the moisutre present in the refuse. In this first phase, aerobic degredation occurs as oxygen is converted to carbon dioxide (Eq 2.6) as microbes use the soluble sugars available as a carbon source (Palmisano and Barlaz, 1996). Nearly all gas in this phase is carbon dioxide. In addition, nitrate is consumed in this phase to nitorgen gas as seen in Eq. 2.7 (Barlaz et al., 1989). The organisms responsible for the degreadation are introduced into the landfill primarily through soil for daily and final cover, wastewater treatment plant sludge, and recycled leachate (Tchobanoglous and Kreith, 2002).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad \text{(Eq. 2.6)}$$

$$5C_6H_{12}O_6 + 24H^+ + 24NO_3^- \rightarrow 42H_2O + 12N_2 + 30CO_2 \qquad \text{(Eq. 2.7)}$$

(Barlaz et al., 1989)

The second phase of landfill gas production occurs when the oxygen is depleted, leaving an anaerobic environment. CO_2 gas is rapidly produced as well as peaks and H_2 gas is also produced in this phase, as seen in Figure 2.6. The time it takes for CO_2 to peak varies between different landfills. Also in this phase, CH_4 production does not occur yet. Studies have suggested that this is due to the need for adequate amounts of CO_2 to be H_2 acceptors. In addition, the pH decreases from about neutral to below 6.0. This is thought to be because of the acid fermentation intermediates (carboxylic acids), which accumulate. These acids are made from acid producing bacteria, acetogens and methanogens (Palmisano and Barlaz, 1996). The biological oxygen demand (BOD_5), chemical oxygen demand (COD) and the conductivity of the lechate all increase due to these organic acids dissolving into the lechate. The lechate will also contain heavy metals in this phase because inorganic chemicals tend to become soluble with such a low pH (Tchobanoglous and Kreith, 2002)

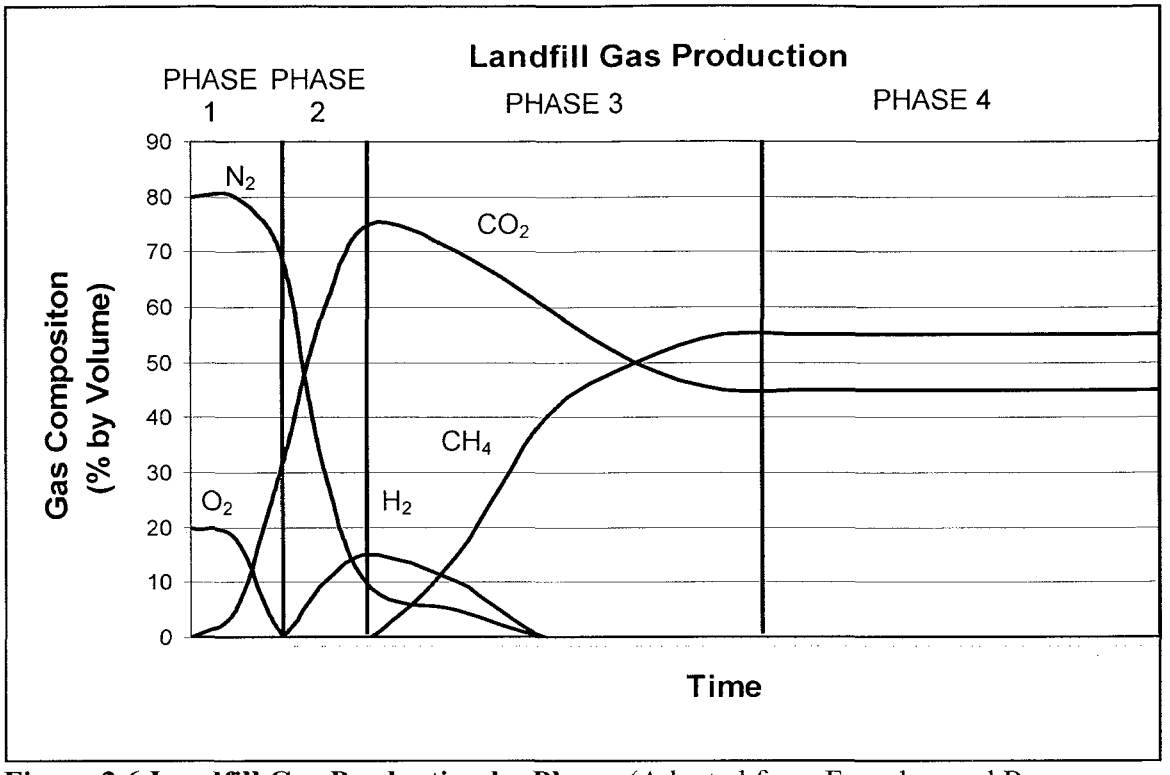


Figure 2.6 Landfill Gas Production by Phase (Adapted from Farquhar and Rovers, 1973)

The next phase involves methanogens rapidly producing of CH_4 while consuming almost all the H_2. The CH_4 is produced from the reduction of the CO_2 with the addition of H_2 as well the conversion of acetic acid (CH_3COOH) into CO_2 and CH_4. In addition, CO_2 and N_2 gases reduce to near steady terminal concentrations (Farquhar and Rovers, 1973). This phase also marks a decrease in accumulation carboxylic acids while the pH increases to levels around 7.9. The increase in pH results in the cellulytic and acetogenic microbes present to also increase in population to levels above those pre-landfilled refuse (Barlaz et al., 1989). The time to have completed the first three phases varies between locations; some simulated landfills have been shown to complete the first three phases in between 180 and 500 days. These tests were conducted in cylinders with refuse, so the results may not be typical (Farquhar and Rovers, 1973).

It is also important to note that the sulfate remains high within the first two phases of refuse decomposition as can be seen from Figure 2.7 The reason for this may be the use of leachate recirculation, as leachate may contain sulfate. The concentration of sulfate then dramatically decreases within the first few weeks at at the landfill. The landfill has a high potential to reduce the sulfate from the refuse. Although Figure 2.7.3 may indicate that the sulfate concentration is reduced to close to zero around day 70, this may not occur as the sulfate may be dissolved in the acidic lechate (Palmisano and Barlaz, 1996).

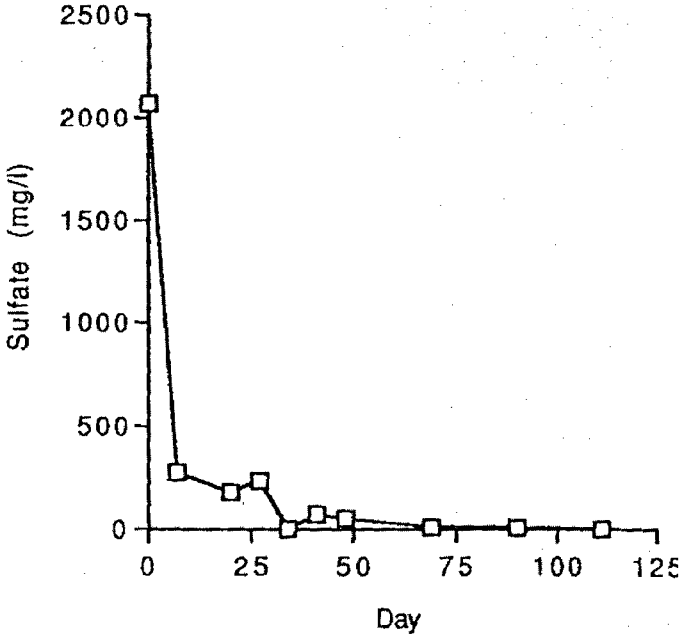


Figure 2.7 Sulfate Concentration in Simulated Landfill Environment (Palmisano and Barlaz, 1996)

The final phase of landfill gas production marks the terminal concentration of different gases including CO_2 and CH_4. The concentrations of CO_2 and CH_4 are between 30-50% and 50-70%, respectively (Figure 2.6). Variations of concentrations of gases can

occur due to environmental factors such as moisture content and pH, as well as from the accumulation of inhibitatory chemicals or the depletion of nutrients (Farquhar and Rovers, 1973). In this phase, the carboxylic acids present drop to concentrations below 100mg/L which increases the pH. However, in this phase, cellulose and hemicellulose decompose more rapidly than in other phases (Palmisano and Barlaz, 1996). This is believed to be true because it is less lignified, therefore, this would be preferred over polymer hydrolysis. The results in the remaining substrate becoming increasingly high in lignin concentration (Barlaz et al., 1989).

2.8 Hydrogen Sulfide Control

There are several techniques used to try to remove H_2S from gases and liquids. They include the use of air stripping, absorption, adsorption, chemical treatment, active biological covers and others. In addition, other treatments to prevent the formation of H_2S have been used in water, wastewater and gas treatment. These treatments include pH elevation, biological treatment, addition of alternative electron acceptors (for the SRB), addition of chemical oxidants, etc (Zhang et al., 2008). One of the main goals of this research has been to evaluate H_2S attenuation in landfill gas passing through different kinds of media, including several different kinds of ashes. Because of previous research (Melendez, 2008), it is believed that one mechanism responsible for H_2S removal in this case is adsorption. Adsorption is often used to remove different materials from a gas or liquid streams. This is done by the mass transfer of substances present in the gas or liquid phase to a solid phase and the removal of these solids (MWH, 2005).

The two types of adsorption are physical adsorption and chemisorption. In physical adsorption, weak bonds, controlled by van der Waals forces, attract the gas molecules (adsorbate) to a solid (adsorbent). In this type of adsorption, the adsorbent can be regenerated, or cleaned of the adsorbate easily by either by the use of heat or pressure reduction (Cooper and Alley, 1994). This type of adsorption is usually rapid. Chemisorption, however, can be slow or rapid, depending on whether the adsorbate is above or below the critical temperature of the adsorbate (Cooper and Alley, 1994). In this type of adsorption, the adsorbate is accumulated on the adsorbent by a chemical bond. It is also not an easily reversible process. For example, the oxidation of SO_3 to SO_2 on activated carbon media is an example of a chemisorption reaction (Cooper and Alley, 1994). In addition, Bandosz found that $H_2S_{(aq)}$ can be oxidized to S^o and SO_2 on the surface of activated carbon and can be seen in Eq. 2.8 and Eq. 2.9 (Bandosz, 2002). These reactions can occur as the H_2S dissolves in the moisture that accumulates on the surface of the adsorbents.

$$H_2S + \tfrac{1}{2} O_2 \rightarrow S^o + H_2O \qquad \text{(Eq. 2.8)}$$

$$H_2S + 3/2O_2 \rightarrow SO_2 + H_2O \qquad \text{(Eq. 2.9)}$$

2.8.1 Adsorption Using Activated Carbon

Many experiments have been conducted to see how or if H_2S adsorbs to activated carbon and can be oxidized to produce elemental sulfur and sulfur dioxide (Bandosz, 2002). Activated carbon is made from different materials which have high carbon content including wood, coal, lignin, coconut shells, etc. These different substances are

used because they have a high surface area to volume ratio and some of the other physical properties can be seen in Table 2.3. The substances then become "activated" by different physical and chemical processes in order to increase the adsorption capacity of the different materials. The materials are dehydrated, carbonized, and oxidized while in a high temperature environment (Cooper and Alley, 1994). In addition, different physical and chemical properties will have an effect on the adsorption capacity of those materials used as adsorbents. These properties include impregnation of various chemicals, pH, water sorption capacity, surface area, porosity, etc (Adib et al., 1999).

Table 2.3 Adsorption Properties of Various Materials*

Composition	Internal Porosity (%)	External Void Fraction (%)	Bulk Dry Density (lbm/ft^3)	Surface Area (m^2/g)
Acid-Treated Clay	30	40	35 - 55	100 - 300
Activated Alumina and Bauxite	30 - 40	40 - 50	45 - 55	200 - 300
Alminosilicate "Sieves"	45 - 55	35	41 - 44	600 - 700
Bone Char	50 - 55	18 - 20	40	100
Carbons	55 - 75	35 - 40	10-30	600 - 1400
Fuller's Earth	50 - 55	40	30 - 40	130 - 250
Iron Oxide	22	37	90	20
Magnesia	75	45	25	200
Silica Gel	70	40	25	320

* (Cooper and Alley, 1994)

Bandosz found that carbons with the greatest adsorption capacity are those impregnated with chemicals. She found in her 2002 study that those activated carbons without impregnation had about 1/3 the capacity as those that are treated with chemicals, except in the case of acidification of the carbons. In addition, in this study, H_2S

adsorption capacity was 2-6 times higher for prehumidified carbons compared to those unhumidified. However, she found that those carbons that were acidified faired more poorly as adsorbents and those carbons pretreated with urea did not seem to have any substantial positive or negative effect. (Bandosz, 2002) The use of caustics (KOH and NaOH) also has the ability to oxidize H_2S. The problem with this, however, is that it results in the deposition of elemental sulfur. This deposition increases the cost to regenerate the carbon because the sulfur becomes trapped in the pores of the carbon. The sulfur also cannot be removed simply by washing with water because elemental sulfur is not soluble in water. If the $H_2S_{(aq)}$ oxidizes to sulfuric acid (H_2SO_4), then it would solubilize and thus be easier it remove (Bagreev et al, 2000).

As previously mentioned, the pH of the carbon affects its adsorption capacity. Bandosz suggests that a carbon a pH of 4.5 or greater will have the best adsorption capacity (Figure 2.8). When the pH is low, only physical adsorption can occur. A greater pH of the carbon will tend to dissociate a larger concentration of H_2S to HS^- ions, which can further be oxidized to SO_2 (Bandosz, 2002). Buffers can be added to the carbon such as ammonia to ensure a high pH. The use of this has shown to increase the adsorption capacity of the carbon (Adib et al, 1999).

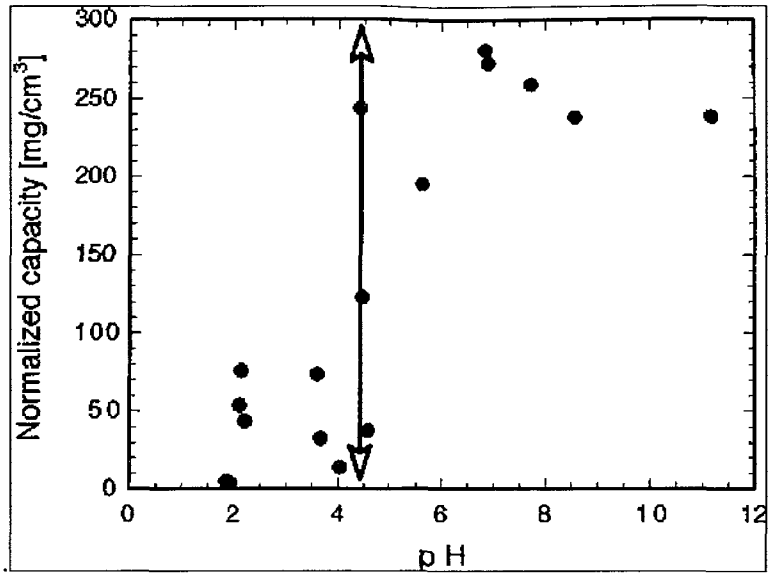


Figure 2.8 Adsorption Capacity of Activated Carbon at pH Values (Bandosz, 2002)

2.8.2 Adsorption Using Ash

Ash is also used as an adsorbent for hydrogen sulfide. Ash may be a more desirable adsorbent for H_2S because it involves reusing what would be a byproduct of combustion (Ducom et al., 2009), and ash may be less expensive than activated carbon. Therefore ash has been added to activated carbon samples to see how the adsorbent properties could be affected. It has been shown that ash, specifically coal ash, may contain may contain activated carbon and metal oxides which have been shown to oxidize or adsorb H_2S (Kastner et al., 2002).

Ash has been found to have a basic pH and because of this, acid/base reactions can occur. Using ash as an adsorbent has a tendency to dissociate the H_2S to HS^- and then S^2, (Ducom et al., 2009) similar to adsorption with activated carbon. This process is completed with H_2S transferring from the gas phase to the liquid phase. Here, the dissolved H_2S may adsorb onto the surface of the ash and dissociate to HS^- and S^{2-} (Kastner et al., 2002). Without the presence of water on the surface of the ash, it is

believed that the dissociation of H_2S cannot be completed. This is because ash tends to be hydrophobic, whereas the dissociation of H_2S occurs in the presence of water (Seredych et al., 2007).

As mentioned, coal ash is found to contain significant concentrations of metal oxides, which include Al_2O_3, Fe_2O_3, TiO_2, etc (Kastner et al., 2002). These can act as catalysts for the oxidation of H_2S (Li et al., 1997). These metal oxides tend to be basic, thus increasing the ability to oxidize H_2S, as previously mentioned. In a study conducted by Seredych et al., it was found that the pH of the ash decreased by at least 1 pH unit. This indicated that there could have been an accumulation of metal salts on the surface of the ash (Seredych et al., 2007).

2.8.3 Chelated Iron Hydrogen Sulfide Removal

One of the common techniques for removal of H_2S from landfills is the use of iron catalyst to oxidize H_2S to elemental sulfur, as seen in Equations 2.10 and 2.11. In this process, ferric iron (Fe^{3+}) is also reduced to ferrous iron (Fe^{2+}). This takes place in a solution as H_2S get dissolved, and where the solution is slightly basic (pH=8.0 to 8.5) (Kohl and Nielsen, 1997). As previously mentioned, the dominant sulfur species will be HS^- with a pH above 7 and below about 12.92. So, in this environment, the hydrogen sulfide will dissociate to bisulfide and a hydrogen ion. LO-CAT is one of the companies that produce a scrubbing device that completes this task. A typical process flow diagram system of the Lo-Cat is shown in Figure 2.9.

A second reaction occurs where the ferrous iron becomes oxidized to reform ferric iron (Eq. 2.12). The overall reaction can be seen in Eq 2.13 as hydrogen sulfide is

oxidized to elemental sulfur and water (Gialet et al., 2004). The iron is not represented in the total reaction because it catalyzes the reaction. In fact, the iron is in the form of chelated-iron as different ligands are complexed with the iron. These ligands include molecules NTA, EDTA, HEDTA, etc (McManus and Martell, 1997). However, the purpose of the chelated-iron is to donate an electron to the disulfide ion and to receive an electron from the oxygen (Eq. 2.8.3.3) (Gialet et al., 2004).

$$H_2S \rightarrow HS^- + H^+ \qquad \text{(Eq. 10)}$$

$$2Fe^{3+} + HS^- \rightarrow 2Fe^{2+} + S + H^+ \qquad \text{(Eq. 2.11)}$$

$$2Fe^{2+} + 1/2O_2 + H_2O \rightarrow 2Fe^{3+} + 2OH^- \qquad \text{(Eq. 2.12)}$$

$$H_2S + 1/2O_2 \rightarrow S + H_2O \qquad \text{(Eq. 2.13)}$$

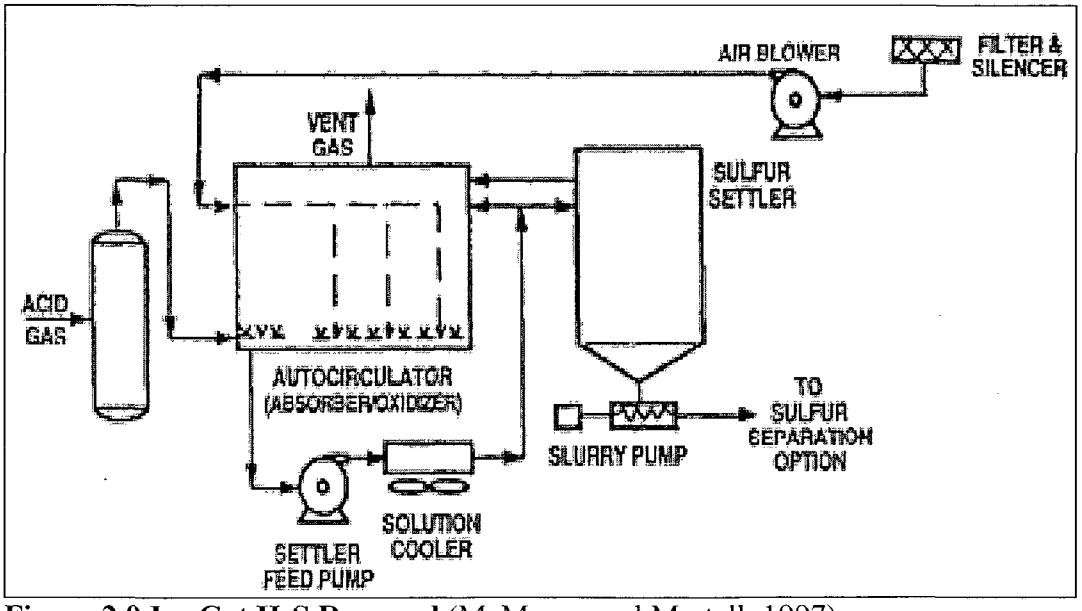


Figure 2.9 Lo-Cat H_2S Removal (McManus and Martell, 1997)

2.9 Hydrogen Sulfide Prevention

One aspect of the research was to see if an increase in pH could prevent the formation of hydrogen sulfide from C&D fines. As previously mentioned, the pK_a's for $H_2S/HS^-/S^{2-}$ are about 7 (6.99) and 12.92 (Benjamin, 2002). Therefore, at a higher pH, (above 7), HS^- will be the predominate species, and above 12.92, S^{2-} will be the predominate species if the species are dissolved in the leachate (which they often are in landfill environment). Lime in the form of $Ca(OH)_2$ as well as quicklime (CaO) have been shown to increase the pH as well as being used to oxidize H_2S (Plaza et al., 2007). In this study performed by Plaza et al., columns were made to simulate a landfill environment where leachate and H_2S samples could be taken. Drywall, which contains $CaSO_4$, was used as a source of sulfur as it has been shown to reduce to H_2S (Fenchel et al., 1998). Different amendments to the drywall were added to see if these could either prevent the formation of H_2S or oxidize H_2S. The different amendments included sand, cement, lime and combinations thereof. In the study, the one column that was found to have low H_2S concentrations also had produced a leachate with a high pH (around 12). Also, the other columns with lime experienced a lag in H_2S production as the pH was also high (Plaza et al., 2007).

H_2S generation can also occur in sewer systems and, as previously mentioned, this can lead to corrosion of pipes as well as health, odor and other environmental issues. The two techniques employed in this area, as well as the research performed in this paper, are to either prevent the formation of H_2S or to somehow remove it from the gas/liquid stream (Figure 2.10) (Zhang et al., 2008). Similar to the experiment by Plaza et al., Zhang et al. investigated the use bases for pH elevation. They noted that the use of sodium hydroxide (NaOH) or calcium hydroxide is sometimes employed to raise the pH

of the liquid stream above 9, thus the main form of H_2S is in the form of HS^-. The problem with raising the pH, however, is that the pH may remain high downstream and be undesirable for future processes (Zhang et al., 2008).

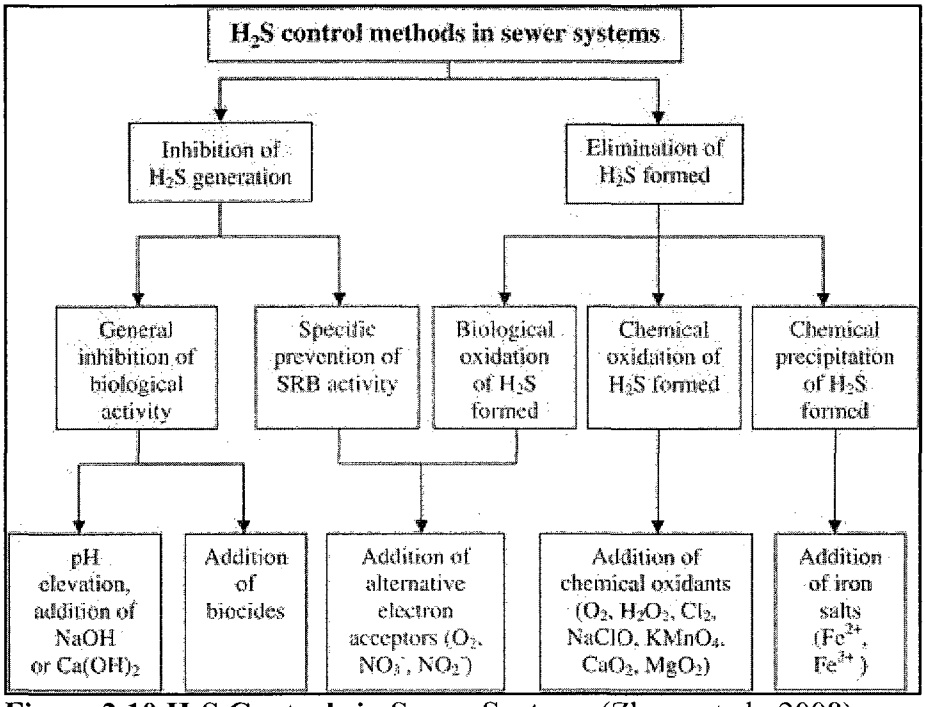


Figure 2.10 H_2S Controls in Sewer Systems (Zhang et al., 2008)

2.10 Materials Investigated

2.10.1 Coal Bottom Ash

Coal bottom ash is produced from the coal that is combusted to create steam for industrial purposes and energy. When the coal is combusted, about 95% is retained and the coal is reduced to about 10% of the original volume, according to the Turner-Fairbank Highway Research Center (TFHRC, 2006). There are three different kinds of ashes produced from this process: fly ash, boiler slag and bottom ash. Fly ash accounts for approximately 74% of the ash generated, and this type of ash is entrained on stack

filters with the flue gases of the coal combustion process. Boiler slag makes up about 6% of the total ash. It is formed when the ash is under intense heat and falls to the bottom of the boiler. Finally, bottom ash accounts for about 20% of the ash and also accumulates on the bottom. It is heavier than the fly ash so it does not become entrained in the flue gases (TFHRC, 2006).

Bottom ash is composed of porous angular particles. The particles are primarily sand-sized, but can be as small as fine sand or as large as fine gravel as can be seen in 13. Between 50 and 90% (by weight) of the ash typically passes a Number 4 (4.75mm) sieve, 10 to 60% typically pass a Number 40 (0.42mm) and 10% or less normally pass a number 200 (0.075mm) sieve. In addition, bottom ash has a specific gravity of 2 1 to 2.7 and weighs about 45-100 lb/ft^3. It is composed of between 45 and 70% (by weight) of SiO_2, between about 15 and 29% AlO_3, between 2 and 15% Fe_SO_3, 0-15% CaO, 1-5.2% MgO, 0.6-1% Na_2O and 0-0.3% K_2O, with usually less than 1% sulfate (TFHRC, 2006) In addition, bottom ash tends to contain large pieces of pyrite, also known as "popcorn" particles. These particles cause the ash to have a lower specific gravity. Bottom ash also may have a low pH, making it corrosive. Therefore, this type of ash may degrade with compaction and may not be as suitable as an aggregate in a highway construction compared to other materials (Griffiths and Krstulovich, Jr, 2002).

Despite this fact, there are several different uses for coal bottom ash, is it is inexpensive and thus desirable. The applications for bottom ash include filler material in embankments, aggregate in road base/sub-base and pavement, feed stock and aggregate in concrete production as well as snow and ice traction on pavement (TFHRC, 2006). In order for the ash to be considered as filler material, it must be near the optimum moisture

content (12-24%), be noncorrosive (pH greater than 5.5), and be screened and/or ground to reduce the size to less than ¾ inch. When using bottom ash in road base/sub-base and pavement, the sizing and moisture content must also be at proper levels. "Popcorn" particles must be removed in this process. In addition, the ash is to be blended with other aggregates. The addition of bottom ash will increase the bearing strength of the base or sub-base (TFHRC, 2006).

It is also important to note the distinction between two different classes of ash. When coal is burned, the byproducts are fly ash and bottom ash (TFHCR, 2006). The American Society for Testing Materials has divided fly ash into two different types, Class C and Class F (ASTM C 618). Class C ash is typically produced from coal from the western part of the United States and is produced from the burning of subbituminous coal and lignite. Class F ash is made from coal in the eastern United States and is produced from the burning of anthracite and bituminous coal (Halstead, 1986). A major difference between the two different classes of ash is the amount of CaO they contain; Class C contains about 30-40% and Class F contains 1-12% (ASTM C204).

2.10.2 Wood Char Ash

Wood-char ash, or wood ash, is another material explored in this research. The physical and chemical properties of wood ash can vary greatly due to several reasons. These include the type of plant and part of plant used, type of soil and climate, as well as collection of ash and storage (Demeyer, et al., 2001). Wood ash can be used as an application to forest floors to increase the pH (Bååth et al., 1995). The result of this study showed that the application of wood ash on the forest floor resulted in the pH of the soil

to increase by about ½ to almost 2 pH units. By raising the pH, it provided a more suitable environment for the microbial community (Bååth et al., 1995).

Physically, 80% of wood ash is less than 1.0mm and can contain all particle sizes from coarse sand and clay. The density of wood ash varies from 0.27g/cm^3 for wood ash and 0.51g/cm^3 for ash from pulp and paper waste. It is believed that the reason that ash from pulp and paper waste has salt and clay additives, which are used in the production of paper (wood_ash.pdf). Calcite ($CaCO_3$) is the most prevalent compound in wood ash. Lime (CaO), riebeckite ($(NaCa)_2(FeMn)_3Fe_2(SiAl)_8$), portlandite ($Ca(OH)_2$), calcium silicate ($Ca_2SiO_4$), hydrotalcite ($Mg_6Al_{12}CO_3(OH)_{16} \cdot 4H_2O$) and serandite ($Na(MnCa)_2Si_3O_8(OH)$) make up a smaller percent of wood ash (Demeyer, et al., 2001).

2.10.3 Lo-Cat Residual/Elemental Sulfur

Lo-Cat residual, which is 88.6% elemental sulfur, is one of the materials evaluated in this research. In the solid form it usually exists as a yellow powder and has a slight odor (Mallinckrodt Baker, Inc, 2006), although with impurities, can possess a strong odor. It is about 2.07 times denser than water and boils at 445°C (Mallinckrodt Baker, Inc, 2006). Although it is generally benign if ingested, it can be flammable and can irritate the skin and eyes (Mallinckrodt Baker, Inc, 2006). As previously mentioned, sulfur is an important part of biosphere as it is transformed and transported by biological and chemical agents. In addition, sulfur is transferred throughout the environment by anthropogenic activities, such as the combustion of fossil fuels (Postgate, 1984).

There are many different uses for elemental sulfur. In 2007, about 8.2 million tons were produced in the United States. Of this, about 60% was used for agricultural

purposes, 25% was produced from petroleum, 3% from metal mining and 12% produced from other sources (Ober, 2008). In the agricultural field, elemental sulfur can be applied as an acidulent for soils that have an undesirably high pH. For example, elemental sulfur is used in rice fields to decrease the pH of soils that groundwater with high Ca, Mg and HCO_3^- made too basic for optimum crop production (Slaton et al., 2001). Elemental sulfur can also be applied to peach crops as a fungicide. It used to prevent peach scab and is preferred as it less expensive than alternative fungicides (Scherm and Savelle, 2001). Sulfur is also often employed in the form of sulfuric acid. About 90% of the sulfur consumed in the United States in 2007 was in the form of sulfuric acid, while the other 10% was in the form of elemental sulfur (Ober, 2008).

Other uses of sulfur include that mercury removal and cotton dyes. Mercury can be added to carbon to attenuate vapor phase mercury (Liu et al, 1998). Mercury is dangerous to humans, fish, and the environment. If sulfur can be added to carbon to remove mercury, then the potential for mercury poisoning can be decreased. In addition, sulfur can be used for making dyes in an environmental friendly manner. This is done by not using chemicals such as Na_2S and $Kr_2Cr_2O_7$. Instead sulfur can be used as an oxidant in the form of $(NH_4)_2S_2O_8$, which would be less hazardous (Ibrahim, 2005).

2.10.4 Lime

Lime ($(CaOH)_2$) as well as quicklime (CaO) were both investigated in this research. Quicklime is produced from the burning of limestone or as product or by-product of industrial process. In addition, lime or calcium hydroxide can be produced by adding water to quicklime, or calcium oxide. Calcium oxide is deemed unstable because

heat is produced when mixed with water, making caution necessary when handling. Calcium hydroxide can form calcium oxide if heated, as water would be lost. If exposed to air, calcium hydroxide can form calcium carbonate by absorbing calcium carbonate (OMRI, 2002). Calcium hydroxide, in the solid form, exists in the form of white powder. Its density is 2.24 g/cm^3, melts at 580°C and its pH in solution is 12.4 (Mallinckrodt Baker, Inc, 2007a). Calcium oxide, however, can appear is white or yellow lumps when in solid form. Its density is 3.37g/cm^3, melts at 2572°C and its pH in solution is 12.5 (Mallinckrodt Baker, Inc, 2007b).

The United States produced about 19.8 million metric tons and consumes about 20 million metric tons of lime and quicklime in 2008. The most prevalent use of lime is steelmaking, followed by flue gas desulphurization, construction, water and wastewater treatment, pulp and paper production, and others (Miller, 2009). Another use of calcium hydroxide, as well as calcium oxide, is in agriculture. The purpose of this, as well as in water treatment, is to increase the pH as calcium hydroxide readily dissociates in water to form Ca^{2+} and OH^- ions (OMRI, 2002). As previously mentioned, the pH of both of these liquids in solution is above 12. Because of this high pH, a common practice has been to use calcium hydroxide on acidic soils as a buffer. Lime is also promising as a buffer because it may be a nontoxic alternative to other buffers (Liu et al., 2004).

2.10.5 Zeolite

For this research, zeolite is desirable because it has been shown to adsorb polar molecules (Mumpton, 1999), which H_2S is. Other uses include concrete aggregate, water and wastewater treatment, nuclear waste treatment, animal nutrition, horticulture and

odor control (Mumpton, 1999). In 2007, about 57,400 metric tons of zeolite were mined in the United States and 57,100 metric tons were consumed were consumed in the United States (Virta, 2008). The price of zeolite can vary, but it generally costs between $50 and $220 per ton. Application and fineness of the zeolite will affect the price, as finer and a higher grade zeolite will be more expensive (Virta, 2008).

As mentioned, zeolite is used to remove adsorb and attenuate molecules. It has an aluminosilicate and porous structure. Because of this porosity, zeolite has the ability to selectively pass certain sized molecules though it (Mumpton, 1999). In addition to essentially "sieving" particles, zeolite has the ability to adsorb polar molecules. The greatest affinity of zeolite to any molecule is H_2O. Because of this affinity, zeolite is commonly employed as a desiccant and other drying applications (Mumpton, 1999). In addition, adsorption techniques by zeolites are often employed to treat biogas. CO_2 and more predominantly, H_2S are can be removed from CH_4 by being adsorbed by the zeolite. Hydrophilic zeolite tends to adsorb H_2S as they fill the pores of the zeolite (Cosoli et al, 2008).

CHAPTER 3

METHODS AND MATERIALS

3.1 Overview

This research included four different experiments: an ex-situ landfill gas experiment to evaluate H_2S attenuation with industrial materials; construction and demolition (C&D) fines analysis; an in-situ landfill simulation to test H_2S formation prevention; and an in-situ landfill simulation experiment to evaluate H_2S generation. The materials for this experiment include C&D fines, four different ashes, lime (calcium hydroxide), quicklime (calcium oxide), foundry sand, zeolite, and sulfur cake. This section includes a detailed description of these materials and the methods used for this research.

3.2 Materials

3.2.1 C&D fines

As previously mentioned, C&D fines are a product of mixed C&D processing and recycling facilities. Fines often have a soil-like characteristic, but also include small pieces of wood, cardboard, concrete, asphalt, drywall, etc. The C&D fines for this research was received from C&D processing facilities (that will remain anonymous) located in Massachusetts, California and Oregon.

3.2.2 Landfill Gas Experiment

Four different ashes were used as adsorbents to test the adsorption of hydrogen sulfide. Ash has been shown to attenuate H_2S (Ducom et al, 2009, Seredych et al, 2008). The ashes used were by-products of different industries. Ash 1 and Ash 2 were both coal bottom ashes from Minnesota. Ash 3 was a wood ash from Minnesota, and Ash 4 was wood ash from New Hampshire.

3.2.3 In-situ H_2S Prevention

Several different materials were investigated in their ability to prevent the formation of hydrogen sulfide. Calcium hydroxide ($Ca(OH)_2$) is a white powder used in several of the experimental columns. The $Ca(OH)_2$ used was reagent grade, containing a minimum of 97.0 to 97.8% $Ca(OH)_2$ and was purchased from Fisher Scientific. Calcium oxide (CaO) (lab grade, Fisher Scientific) is also a white powder used in one the experimental columns. As shown in Table 3.1, the CaO and $Ca(OH)_2$ were both put in the experimental columns at a ratio of 4:1 C&D fines to CaO or $Ca(OH)_2$. Ash 1 was also used for this experiment. This was also placed in a column with a fines to ash ratio of 4:1. Finally, a proprietary zeolite powder from Maine was used in a column. From a previous study, it was found that 2000lb of sulfur disposed of in a landfill can produce about 295lb of H_2S (Anderson et al., 2009). Based upon the sulfur content of the fines, and the attenuation potential of zeolite provided by the manufacturer, a fines to zeolite ratio of 2.5:1 was used. Further data concerning the contents of these columns is located in Appendix D.

Table 3.1 H_2S Prevention Experiment Column Contents

Column	Contents
1	423g C&D Fines
2	393g C&D Fines; 98g Ca(OH)2
3	393g C&D Fines; 98g Ca(OH)2
4	403g C&D Fines; 101g CaO

5	287g C&D Fines; 72g Unused Ash 1
6	311g C&D Fines; 123g Zeobloc

3.2.4 In-situ H_2S Regeneration

Another test was conducted to see if hydrogen sulfide could be regenerated from the landfilling of materials from processes used to attenuate hydrogen sulfide. One of the materials tested was sulfur cake from a landfill in South Florida. This sulfur cake was a byproduct of H_2S removal from landfill gas by the use of an iron catalyst (Lo-Cat), which was discussed in the Literature Review. The cake contained approximately 88.6% sulfur, the remainder contained various other elements. Five grams of sulfur cake were added to the "simulated" landfill material (organic material that would degrade) – a mixture of paper and dog food (Table 3.2). Shredded paper and dog food also were used in order to provide a carbon source for the H_2S to be formed (Yang et al., 2006).

As shown in Table 3.2, four other columns constructed contain 10g of the four ashes used as adsorbents (exhausted) in the landfill gas experiment. Five grams of dog food and varying amounts of paper were used in these columns. Column 7 contained shredded paper and dog food as well as exhausted Zeo-BLOC™ paper. The Zeo-BLOC™ paper was made from recycled paper shown to remove H_2S odors (Bishop et al, 2007). The Zeo-BLOC™ paper had already been used to remove H_2S odors. Further data on the columns can be found in Appendix C.

Table 3.2 H_2S Regeneration Experiment Column Contents

Column	Contents
1	13.4g Paper; 5g Dog Food (Control)
2	13.3g Paper; 5g Dog Food; 5g Sulfur Cake
3	12.8g Paper; 5g Dog Food; 10g Used Ash 1
4	13.1g Paper; 5g Dog Food; 10g Used Ash 2
5	12.2g Paper; 5g Dog Food; 10g Used Ash 3

6	12.5g Paper; 5g Dog Food; 10g Used Ash 4
7	3.4g Paper; 5g Dog Food; 10g Zeobloc Paper

3.3 Methods

3.3.1 Landfill Gas Experiment

3.3.1.1 Column Construction

The first experiment is an ex-situ test conducted to see if H_2S can be attenuated using any of the aforementioned four ashes. The experiment was conducted at a landfill gas well use using a clear or white PVC column in 2 or 4 inch diameters as seen in Figures 3.1a and 3.1b. The lengths were either 20.125 inches or 36 inches. In these columns, aggregate comprised of inert crushed stone or glass beads were placed in the bottom of the column in order to avoid preferential paths for the H_2S to travel. In this way, kinetics can be improved as the gas will tend to distribute throughout the cross-sectional area. A plastic mesh was placed above this in order to keep the ash, which is placed above the aggregate, from being lost out the bottom of the column. A 1/4inch diameter inlet and outlet were placed on the top and bottom of the column and connected to plastic tubing. In addition, a valve was placed 16 or 32 inches from the bottom of the column (near the top of the column), where sampling could take place.

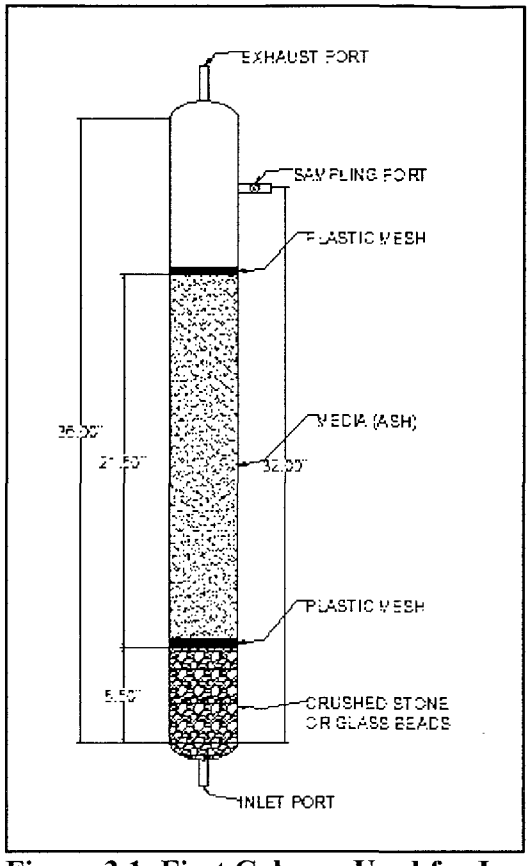


Figure 3.1aFirst Column Used for Landfill Gas Experimentation

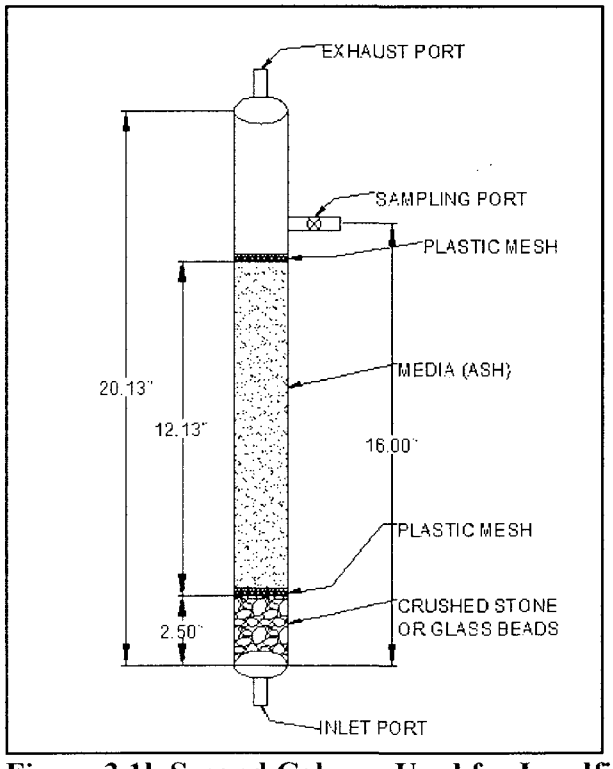
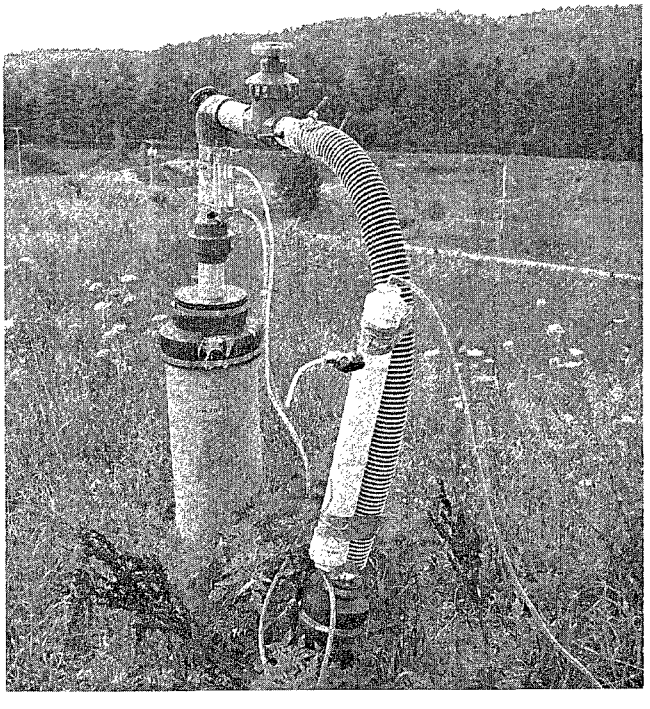


Figure 3.1b Second Column Used for Landfill Gas Experimentation



3.3.1.3 Gas Analysis

The concentration of H_2S was measured before the landfill gas entered the column and after the gas exited the column. In addition, the concentrations of methane, (CH_4), were analyzed at the same locations in order to evaluate if the material in the column attenuated CH_4 as well. To measure the concentration of H_2S, a Jerome 631-X (Arizona Instruments) was used for concentration of H_2S below 50ppm, and RAE gas detection sticks (RAE Instruments) were used for concentrations above 50ppm. Verification of the Jerome 631-X was performed as the instrument was zeroed and the ambient air was checked. For quality purposes, the accuracy the detection sticks were checked against the Jerome 631-X and often run in duplicate. Also,in order to check the concentration of CH_4, a landfill employee used a Gem-500 (CES-LANDTEC) to measure methane content of landfill gas before it entered the column and after the gas exited the column.

3.3.1.4 BET Analysis

A test was conducted to determine the surface area to mass ratio of the ash. All ashes except one (Ash 4), were analyzed. The apparatus that measured the surface area failed after the surface area of three of the ashes were determined. As previously mentioned, the different ashes were thought to have similar properties of activated carbon. Adsorbent surface area is believed to be proportional to adsorptive capacity (Bandosz, 2002). The apparatus used for this analysis was the TriStar 3000 (Micrometrics).

3.3.1.5 pH of Ashes

As previously mentioned, H_2S adsorption is influenced by pH. In order to find the pH of the ash, 250mL of water treated by reverse osmosis (RO water) was added to

50g of each ash. The ash/RO water mixture was then covered and stirred for 1hour and the pH of the mixture was measured.

3.3.2 C&D Fines Analysis

3.3.2.1 Sulfate

The C&D fines that were collected were tested in order to determine the sulfate content. The leaching standard operating procedure (SOP), which was developed at the University of Florida, was used for this test (Musson, et al., 2008). After the test, the leachate from the fines was sent to a laboratory (Resource Labs, Inc. (RLI), Portsmouth, NH) to determine the sulfate content by ion chromatography.

3.3.2.2 Moisture Content/Organic Carbon Content

The moisture content of various materials was determined because the amount of moisture present can impact biological activity and therefore, the amount of H_2S produced (Gurijala et al., 1997). To determine percent moisture, the mass of a metal container was weighed, then the fines or other material was added, and the container was again weighed. The container was placed in a 100°C oven for 24 hours and weighed. The moisture content was determined to be the mass of the fines before being in the oven minus the mass of fines after being in the oven, divided by the mass of the fines before being in the oven. In addition, the organic and inorganic carbon was determined by a method called loss on ignition (LOI) (Dean, 1974). This method is conducted in a similar manner to moisture content. The organic carbon and inorganic carbon present were determined to be volatized to carbon dioxide and ash at 550°C and 1000°C, respectively. Therefore, using a two-step process of heating, the difference in weight can be used to determine the organic and inorganic carbon.

3.3.3 Columns for Testing In-situ H_2S Prevention

3.3.3.1 Column Construction

The columns used for this experiment were 15 inches in length and 2inches in diameter, as seen in Figure 3.3.. The bottom 3 inches of the column contain glass beads, which are used to collect excess leachate, so as not to saturate the media above the beads. Above the beads is a plastic mesh screen to separate the beads from the materials in the column. A 1/4inch valve was placed on top to add RO water treated by reverse osmosis, which would simulate rainwater keeping the contents moist. A 1/4inch valve was also placed on the bottom of the column to collect the leachate. Valves were also placed on the side of the column in order to sample the gas inside the column.

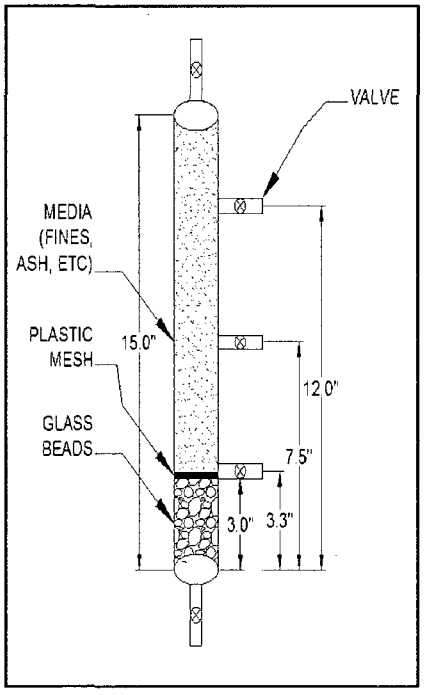


Figure 3.3 Column Used for H_2S Prevention/Regeneration

3.3.3.2 Parameters monitored

3.3.3.2.1 Leachate

The columns that were used for in-situ prevention created leachate. Approximately 100mL RO water was added daily and the leachate was checked and collected every day until the column reached field capacity. After this point, 24mL RO water was added daily for 5 days and the leachate was drained and analyzed weekly. A final procedure included the addition of 100mL RO water weekly, while the leachate was drained and analyzed weekly, as well. Several different characteristics of the leachate were determined in order to assess the biological activity in the column. The characteristics of the leachate that were analyzed were pH, oxidation reduction potential (ORP), dissolved oxygen (DO), sulfide (S^{2-}), and sulfate (SO_4^{2-}). A YSI 556 Probe (GENEQ) was used to determine the pH, ORP, and DO in mg/L and percent saturation. These parameters were used as indicators for SO_4^{2-} reduction. The leachate was then tested for S^{2-} with a DR/2000 Spectrophotometer (HACH Method 8131). The purpose of the S^{2-} test was to determine if biological activity, specifically sulfate reducing bacterial activity, was occurring. The leachate was also tested for SO_4^{2-}, outsourced to a separate laboratory (RLI) for analysis. Sulfate is an important parameter as it is reduced by the sulfate reducing bacteria.

3.3.3.2.2 Gas

In this experiment, the only gas that was of concern was H_2S. Similar to the ex-situ landfill gas experiment, gas samples were also collected using a Jerome 631-X. These gas samples were also an indication of if and/or how much SO_4^{2-} was being reduced.

3.3.4 Columns for Testing Regeneration of H_2S

3.3.4.1 Column Construction

The columns were constructed in the same way as the columns for the in-situ H_2S prevention experiment. They have the same dimensions, and their contents can be seen in Table 3.2

3.3.4.2 Parameters monitored

3.3.4.2.1 Leachate

Similar to the in-situ H_2S prevention experiment, the leachate was collected on the same schedule. The parameters pH, ORP, DO, sulfide and sulfate were also measured using the same techniques. The reason that these parameters were measured was that it was necessary to see if biological activity was occurring in this experiment as well.

3.3.4.2.2 Gas

In this experiment, the only gas that was of concern was H_2S. Similar to the ex-situ landfill gas experiment, gas samples were also collected using a Jerome 631-X. These gas samples were also an indication of if and/or how much SO_4^{2-} was being reduced.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Overview

This section presents and discusses the results of the four experiments conducted: the ex-situ landfill gas experiment, the C&D fines analysis, the H_2S prevention experiment and the H_2S regeneration experiment.

4.2. Ex-situ Landfill Gas Experiment

The first experiment is the ex-situ landfill gas experiment, and the goal of this experiment was to determine what the extent different ashes attenuated H_2S from landfill gas. The results from the various parameters measured in the ex-situ landfill gas experiment will be presented and discussed in the following section and include pH, surface area, moisture and H_2S attenuation. In addition, an evaluation was conducted to determine if CH_4 was also attenuated by the adsorbents.

4.2.1. pH Determination

The pH of the different ash columns can be seen in Table 4.1. All the ashes, except Ash 2, produced a basic leachate when mixed with reverse osmosis treated water. The determination of the pH of the ash is significant because it can be an indication of the ability of the ash to attenuate H_2S. It is proposed that one of the mechanisms responsible for the attenuation of H_2S is adsorption. For adsorption to occur, it is believed that a

water layer is necessary on the surface of the ash where the H_2S could transfer from the gas phase to the liquid phase (Bandosz, 2002). In the presence of water, the H_2S will dissociate to HS^- ions if the ash, especially if the environment is slightly basic. This is due to the fact that the pK_a's for the sulfur species are about 7 and 13 (Adib et al, 1999). So, the predominate species of sulfur are H_2S at a pH below 7, HS^- at a pH above 7 and below 13, and S^{2-} at a pH above 13.

Table 4.1 Ash pH Values

Sample	Mass (g)	RO Water Added (mL)	pH
Ash 1	50	250	8.37
Ash 2	50	250	6.36
Ash 3	50	250	9.24
Ash 4	50	250	11.67

If bottom ash is used to attenuate H_2S and the ash is basic in solution, then the H_2S may further dissociate HS^- ions into S^{2-} ions (Ducom et al., 2009). However, if the ash is acidic, then the H_2S will not tend to dissociate but the few HS^- ions that do exist at a slightly acidic pH will oxidize to sulfur dioxide and then form sulfuric acid (Bandosz, 2002). For oxidation to occur, the pH can only be as low as 4.5, according to Bandosz. At a pH below this threshold, the concentration of HS^- is extremely low, and only physical adsorption can occur. In this case, the adsorption capacity is not as high as would be if the pH were higher. This tends to be a problem when the adsorbents, specifically activated carbon, are impregnated with different chemicals (Bandosz, 2002). However, the materials used for adsorbents in this experiment were solely natural ashes, not impregnated with any chemicals.

4.2.2. Surface Area of Ashes

The surface areas of the different ashes analyzed are shown in Figure 4.1. It appears that the wood ash columns (Ash 3 and Ash 4) have a greater surface area than the coal ash columns. This is important as a larger surface area aids in the oxidation of H_2S (Bandosz, 2002; Kastner et al, 2003). However, it is suggested that surface area is not the most crucial factor in the ability to remove H_2S from gas streams using activated carbon. This conjecture was hypothesized earlier that activated carbon works similar to the ash. Bandosz (2002) states that the presence of a water film and a basic surface are more important than the amount of surface area. In one case, the amount of surface area was proportional to the H_2S attenuation capacity; however, this carbon was treated with ammonia. It has been shown that treating carbon with ammonia prior to using it for H_2S removal will result in the carbon removing more H_2S if the activated carbon has less surface area (Lee and Reucroft, 1999).

While surface area is important in the oxidation of H_2S, it is also important in the physical adsorption of H_2S (Yan et al, 2002); the surface area of activated carbon used for adsorption is typically $750m^2/g$ to $1800m^2/g$ (Faust and Aly, 1998). The surface areas of the ashes used in this research were less than these typical values for activated carbon (Figure 4.2.2.1). However, the surface area is not the only factor in determining the adsorption potential of the adsorbent. The results of this study show that Ash 1, which did not have the greatest surface area, was able to attenuate the greatest amount of H_2S, (Table 4.4). Reasons for this will be discussed further in this section.

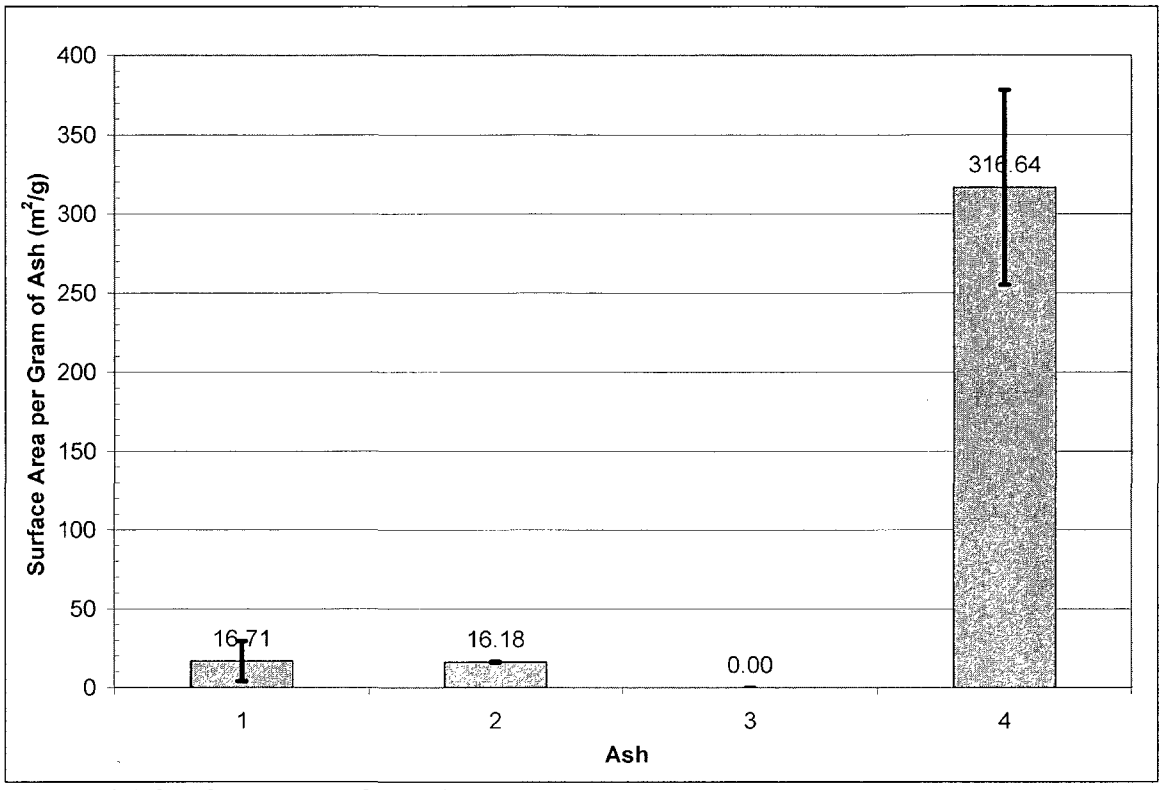


Figure 4.1 Surface Area of Ash Samples

4.2.3. Moisture Content of Ash Samples

The moisture content of each ash sample can be seen in Table 4.2. Recall that Ash 1 and Ash 2 are both coal ashes and from the table, they have similar moisture contents. However, the difference between Ash 3 and Ash 4, which are both wood ashes, is substantial. This could be due to the different geographic location from which they came, or the exact process by which they were produced. Regardless, when the experiment was conducted, significant moisture was noticed in the landfill gas that entered the columns containing the ash samples. Similarly, large amounts of moisture were noticed in the exhaust port as well the sampling port. For this reason, the moisture content of each ash sample may not be significant due to the fact that the landfill gas contained moisture. Moisture is important in the mechanism responsible for attenuating

H_2S from the ash. As previously mentioned, the dissociation of H_2S to HS^- on ash takes place in the presence of water (Adib et al, 1999; Ducom et al, 2009). So, for the oxidation or removal of H_2S to occur on the surface of the ash, the requirements are water on the surface of the ash and a basic pH.

Table 4.2 Moisture Content of Ash Samples

Ash	Moisture Content
1	22%
2	24%
3	4%
4	69%

4.2.4. H_2S Removal/Conversion

Table 4.3 includes the parameters for conducting the landfill gas experiment. This table indicates that because it has the greatest density and mass, Ash 2 should have the capacity to attenuate the greatest quantity of H_2S and the time for Ash 2 to reach exhaustion would be the longest. Conversely with the highest average landfill gas flow rate and highest average H_2S concentration at the sampling well, it appears that Ash 1 would reach exhaustion more quickly than the other ashes.

Table 4.3 Comparison of Landfill Gas Samples

Sample	Mass Sample (g)	Density (g/cm^3)	Average LFG Flow Rate (LPM)	Average Well H_2S Conc (ppm)
Ash 1	400.0	0.36	21.1	1761
Ash 2	600.0	0.73	16.3	1289
Ash 3	222.5	0.19	11.3	1423
Ash 4	134.2	0.08	18.4	1300

However, as shown in Table 4.4, Ash 1 attenuated the greatest amount of H_2S, at approximately 74 mg of H_2S per gram of ash. Recall that both Ash 1 and Ash 2 are both coal ashes, while Ash 3 and Ash 4 are wood ashes. Although Ash 1 and Ash 2 are both coal ashes, there is a large variability in coal combustion. Ash varies by the type of coal burned as well as the design of the power plant. The second point holds true for wood ash as well; the ash can be greatly impacted by the design of the combustion facility. So, although Ash 3 and 4 are both wood ash, Ash 4 attenuated about four times the amount of H_2S that Ash 2 and Ash 3 did (approximately 12 milligrams of H_2S per gram of ash). In addition, Ash 1 was able to attenuate more H_2S per cubic centimeter than could the other ashes. Ash 4 does not attenuate as much H_2S in terms of mass of H_2S per ash volume because of its low density. Ash 4 would be an impractical ash to attenuate H_2S compared to Ash 1 and Ash 2, based on the volume of ash required to attenuate an equal amount of H_2S.

Table 4.4 Total Normalized Hydrogen Sulfide Attenuated

Sample	Total Hydrogen Sulfide Attenuated (mg/g)	Total Hydrogen Sulfide Attenuated (mg/cm^3)
Ash 1	73.80	26.57
Ash 2	11.82	8.63
Ash 3	11.42	2.17
Ash 4	45.04	3.71

Figure 4.2.4.1 displays how long each sample was operated until it reached exhaustion (i.e., the concentration of H_2S at the sampling port of the experimental column was the same as the concentration of H_2S at the gas well). Ash 1 took the longest time to reach exhaustion, which agrees with the results from Table 4.4. Likewise, Ash 4, which

is a wood ash, took the second longest time to reach exhaustion. It is important to note that the attenuation of H_2S per gram of ash presented in Figure 4.2 is also influenced by the variation of landfill gas flow rate and concentration of H_2S.

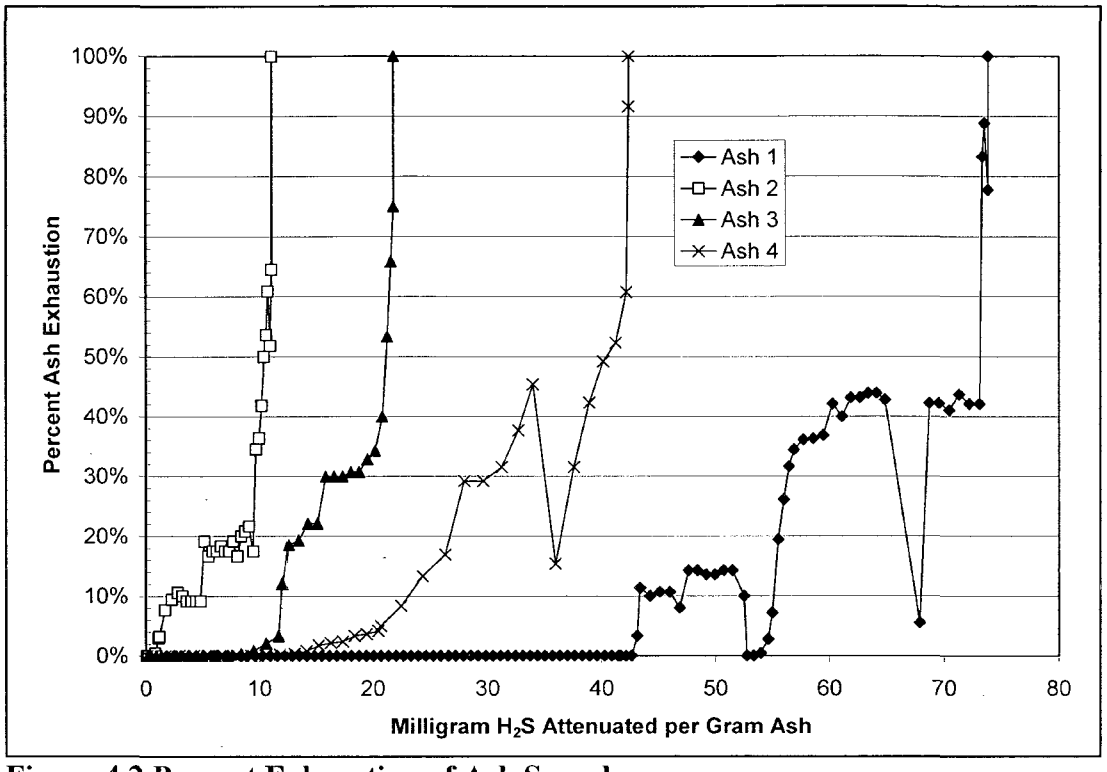


Figure 4.2 Percent Exhaustion of Ash Samples

It is worth noting the shape of the curves. A lag occurs from when the experiment begins to when the sample starts to become exhausted. This is especially visible for the curves made by Ash 1. This lag indicates that virtually 100% of the H_2S passing through the sample was attenuated at this time. After this lag, the exhaustion of these samples seem to rapidly increase before stabilizing for a moment of time, and then increased rapidly again until each of these samples finally reached exhaustion. The curves for Ash 1 and Ash 4 have points at which attenuation increased during the course of the experiment. In the case of Ash 1, a mechanical failure in the pump resulted in the experiment being restarted. It is believed that when this occurred, the preferential

pathway of the landfill gas in the column may have changed slightly, thereby coming into contact with different ash, increasing the ash's ability to attenuate H_2S. In the case of Ash 4, it is possible that the preferential pathway may have changed as well. However, there was no pump malfunction; the pathway may have changed due to the ash being moved by the force of the landfill gas itself flowing through the column.

It is suspected that metal ions and metal oxides may play a role in the attenuation of H_2S. The metal ions may be catalysts in the conversion of H_2S to sulfides (Kastner et al, 2003). Research has suggested that once the H_2S dissolves on the water film surface of the ash, it dissociates to S^{2-}. Another possible scenario is that metal cations present from the ash can react with sulfide to produce metal sulfides (Kastner et al, 2003). This can be seen from in Eq 4.1, Eq 4.2 and Eq 4.3 (Kastner et al, 2003). In Eq 4.1, the first dissociation of H_2S occurs in the presence of a base to produce HS^- ions. In the second dissociation, HS^- reacts with a hydroxide ion to produce a sulfide ion and water (Eq 4.2). Finally, the sulfide ion reacts with metal ions present in the ash (Me^+) and produce metal sulfide.

$$H_2S + OH^- \rightarrow HS^- + H_2O \qquad \text{Eq 4.1}$$

$$HS^- + OH^- \rightarrow S^{2-} + H_2O \qquad \text{Eq 4.2}$$

$$S^{2-} + 2Me^+ \rightarrow MeS \qquad \text{Eq 4.3}$$

As previously mentioned, coal bottom ash contains concentrations of metal oxides including greater than 45% SiO_2, at least 15% AlO_3, between 2 and 15% Fe_2O_3, up to 15% CaO and about 1% of MgO, Na_2O and K_2O (TFHRC, 2006). However, because Ash 1 and Ash 2 were both coal ashes from Minnesota, it is assumed that they were Class C ash. Therefore, the concentration of CaO should be 30-40% (ASTM C204). It is

believed that a moist, aerobic environment would be suitable for metal oxides such as CaO and MgO to react with H_2S (Bagreev and Bandosz, 2005). These authors also theorize that in the presence of CO_2, which landfill gas contains, these metal oxides are converted to bicarbonates and carbonates. The carbonates can act as a buffer and keeping the pH high (above 10) to provide a more suitable environment for H_2S dissociation to occur (Bagreev and Bandosz, 2005).

Another mechanism possibly involved in the attenuation of H_2S with coal ash may also be a function of the presence of CaO. Literature suggests that CaO reacts with a water film, if present on the ash to form $Ca(OH)_2$. The $Ca(OH)_2$ then reacts with $H_2S_{(aq)}$ to form $Ca(HS)_2$ and water. The $Ca(HS)_2$ then can react with oxygen, if present, to produce elemental sulfur and $Ca(OH)_2$, thus keeping the pH high and suitable for further H_2S oxidation (Seredych et al, 2008). This process may result in yellow sulfur deposits in the spent adsorbent. However, there was no indication of elemental sulfur deposit through visual inspection.

As previously discussed in Chapter 2, the use of an iron catalyst to oxidize H_2S to elemental sulfur is sometimes employed. The ferrous iron (Fe II) reduction to ferric iron (Fe III) has been happening to oxidize H_2S from volcanic activity to elemental sulfur for millions of years (McManus and Martell, 1997). Using this as an example, scientists and engineers use this concept to remove H_2S from gas streams. Therefore, it is suspected that iron present in ash has aided in the conversion of H_2S to elemental sulfur (Kastner et al, 2002; Kastner et al, 2003). Moreover, the type of iron that may be responsible for the conversion of H_2S is believed to be Fe_2O_3, which, when reacts with H_2S produces Fe_2S_3 and H_2O (McManus and Martell, 1997). Because coal ash is reported to have up to 15%

Fe_2S_3 present, there is potential for the iron to be responsible for in the attenuation of a portion of the H_2S in the gas stream.

4.2.5. Concentrations of Other Landfill Gases

The concentrations of different gases were measured before entering and after exiting the column, (Table 4.5). It appears that the concentration of CH_4, CO_2 and O_2 were not affected by the coal ash attenuating the H_2S. In addition to this, the concentration of the remainder of the gases (balance), which, other than the H_2S and other trace gases that would not register on the GEM, is mostly inert nitrogen, was relatively unchanged.

Table 4.5 Concentrations of Other Gases of Concern at the Landfill Gas Well and at the Sampling Port of the Experimental Column

Gas	Percent Gas	
	Gas Well Port 1	Exhaust from Column
CH_4	52.7	52.5
CO_2	18.4	22.6
O_2	0.02	0.06
Balance	26.7	23.4
Total	97.82	98.56

In this experiment, it was important to investigate if other gases, specifically (CH_4), were attenuated. The goal of this experiment was to attenuate of H_2S, only because CH_4 can be beneficially used. CH_4 from LFG is often combusted and used to create energy so the removal of it could negatively affect the operation of the landfill. It was important to document that H_2S was attenuated while CH_4 passed through the column unaffected, still allowing beneficial use of the LFG to produce energy.

4.3. C&D Waste Analysis

4.3.1. Overview

In the following section, C&D debris fines are characterized for sulfate, H_2S production, as well as moisture and carbon content. In the first part of this section, the results of an experiment that compiled sulfate content of the C&D fines from C&D processing facilities is presented and discussed. The second part of this section presents the sulfur from the C&D fines that has been put in a landfill in comparison to the amount of H_2S and sulfur that resulted in the landfill gas. The final part of this section presents the results of a loss on ignition (LOI) procedure on several samples of C&D fines. The results of this procedure include the moisture content, organic carbon content and inorganic content of the fines.

4.3.2. Sulfate Content of C&D from C&D Processing Facilities

Figure 4.3 presents the sulfate content of the C&D fines produced at different C&D processing facilities. The facilities include eight from Massachusetts, two from California and one from Oregon. As can be seen in Appendix B, the sulfate contents of the fines from each facility range from about 1.6% to about 15.2%, with an average of 5.92%. The concentrations of sulfate are significant as the C&D fines may be disposed of in a landfill, often with waste or as a cover material. The production of H_2S is caused by the biodegradation of the sulfate by sulfate reducing bacteria, as discussed earlier.

Therefore, the concentration of sulfate (as a source of H_2S) is an important characteristic of C&D fines to document.

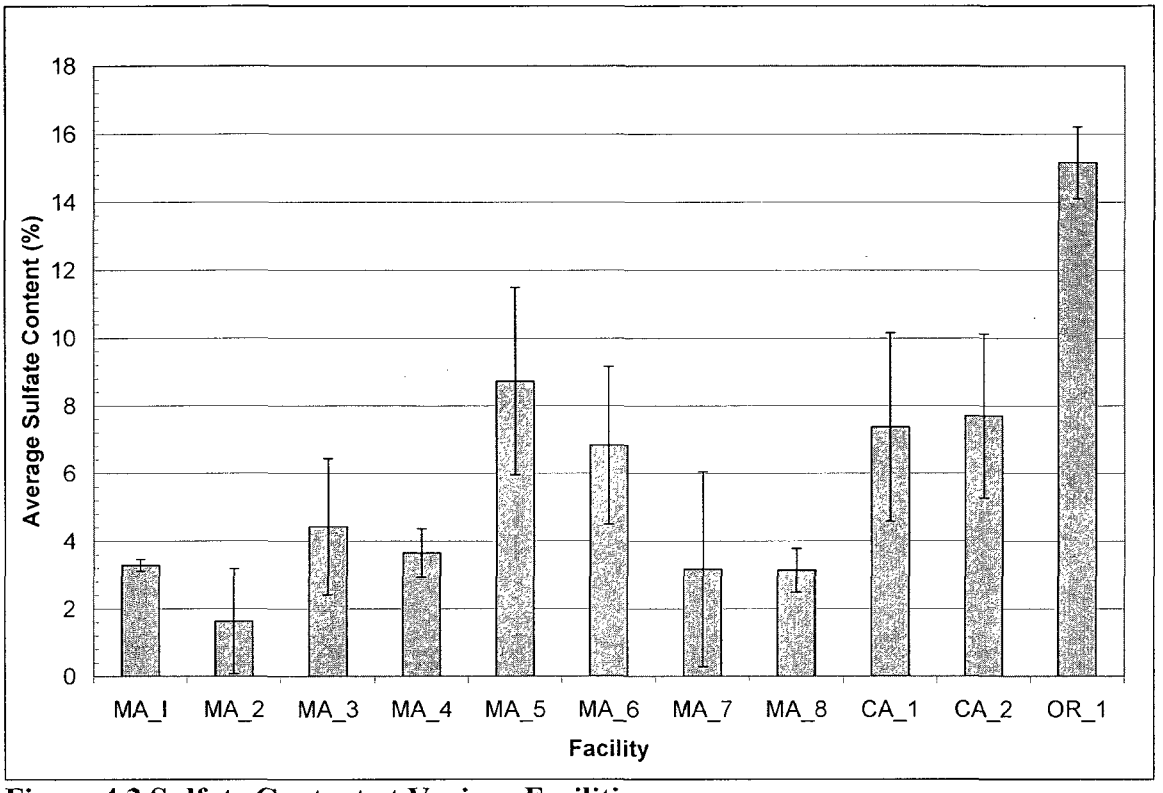


Figure 4.3 Sulfate Content at Various Facilities

The concentration of sulfate in the fines is a function of how the C&D processing facility is operated. If C&D processing facilities recycle more materials from the waste stream, then the percentage of sulfate may be "concentrated" as more materials are removed for beneficial use, but the sulfate (from gypsum drywall), remains. The material that exists in the C&D fines include soil, wood, paper, concrete, metal and gypsum drywall (Jang and Townsend, 2001, Musson et al, 2007). Certain facilities may mechanically screen out or sort out a larger amount of material, thereby concentrating the amount of sulfate from gypsum drywall (if drywall is in the waste stream). However, if the C&D processing facility removes the other materials from the waste stream for

recycling thereby producing fines with a large concentration of sulfate, the amount of fines will likely be less. Likewise the opposite may be true if the fines contain little sulfate. Ultimately, not only is the concentration of sulfate in the fines important, but the quantity of fines placed in the landfill as well, determines the mass of sulfate as a potential "source" which relates to the amount of H_2S that can be produced. This will be illustrated further in the following section.

4.3.3. Comparison of Sulfur Input from C&D Fines and Sulfur Output from H_2S Gas at Several Landfills

Graphs (4.4, 4.5 and 4.6) illustrate the quantity of sulfur placed in three different landfills from the use of C&D fines as ADC, the graphs also show the quantity of sulfur output in the form of H_2S in the landfill gas and the H_2S concentrations observed in the landfill gas collection system (e.g., at the flare). Describing when and how much H_2S can be produced from an input of C&D fines could be beneficial for landfill owners and operators to know. As mentioned, H_2S is undesirable in landfill gas. A more efficient preparation of the removal of the H_2S from the landfill gas could be done if the operator of the landfill could estimate the concentration of H_2S over the course of the landfill's life based upon what was put into the landfill.

From the data given, it appears as though there is a lag between the input of C&D fines and the H_2S readings. Figures 4.4 and 4.6 show that in Site 1 and Site 3, the highest H_2S concentrations after most of the C&D fines were disposed of. Figure 4.5 indicates the greatest amount of H_2S was produced after the C&D fines were placed in the landfill. Because of this discrepancy, it is not clear the exact correlation that exists between the

C&D fines and the production of H_2S. In addition, the high concentrations of H_2S may only be high at specific areas of the landfill, whereas the H_2S data is from an entire section, if not the entire landfill. This may be due to where the C&D fines were placed or where other things that can produce high H_2S concentrations such as sewerage were disposed of.

Site 1 and Site 2 landfills did not have H_2S data until most of the C&D fines were disposed of. The sulfur from the H_2S in the landfill gas on the following graphs seems relatively negligible with the amount of sulfur present in the C&D fines. The amount of sulfur from the H_2S is about two orders of magnitude less than that of the C&D fines indicating that the sulfur still must be in the sulfate form, which the fines were believed to be in, or the sulfur is in another form other than H_2S.

The molar equivalent of sulfur from the H_2S in the landfill gas is also plotted on Figures 4.4-4.6. The amount of sulfur produced from H_2S in the landfill gas in any of the three sites studied is a maximum of one percent of the sulfur input in the landfill in the C&D fines (Table 4.6). Therefore, seeing the trend of which years produced the most sulfur from the H_2S in the landfill gas seems almost negligible compared to the amount of sulfur put in the landfill in the C&D fines.

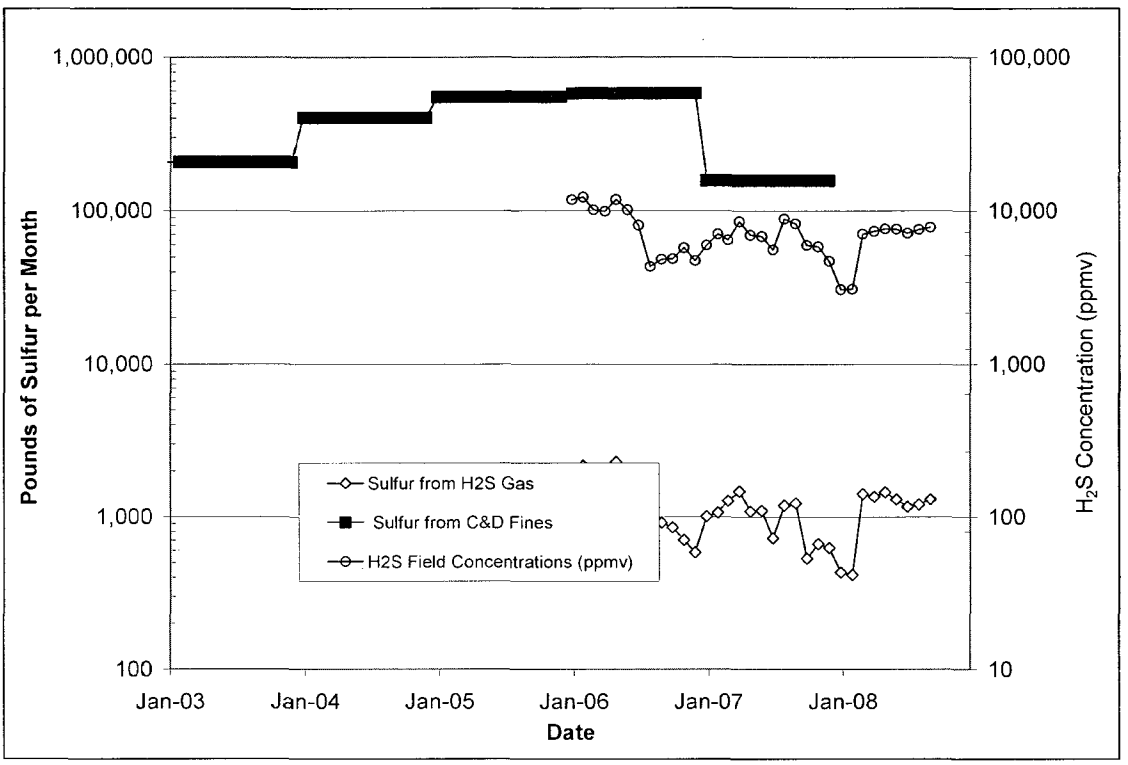


Figure 4.4 Comparison of Input of Sulfur from C&D Fines with H_2S Concentration in Landfill Gas at Site 1 Landfill

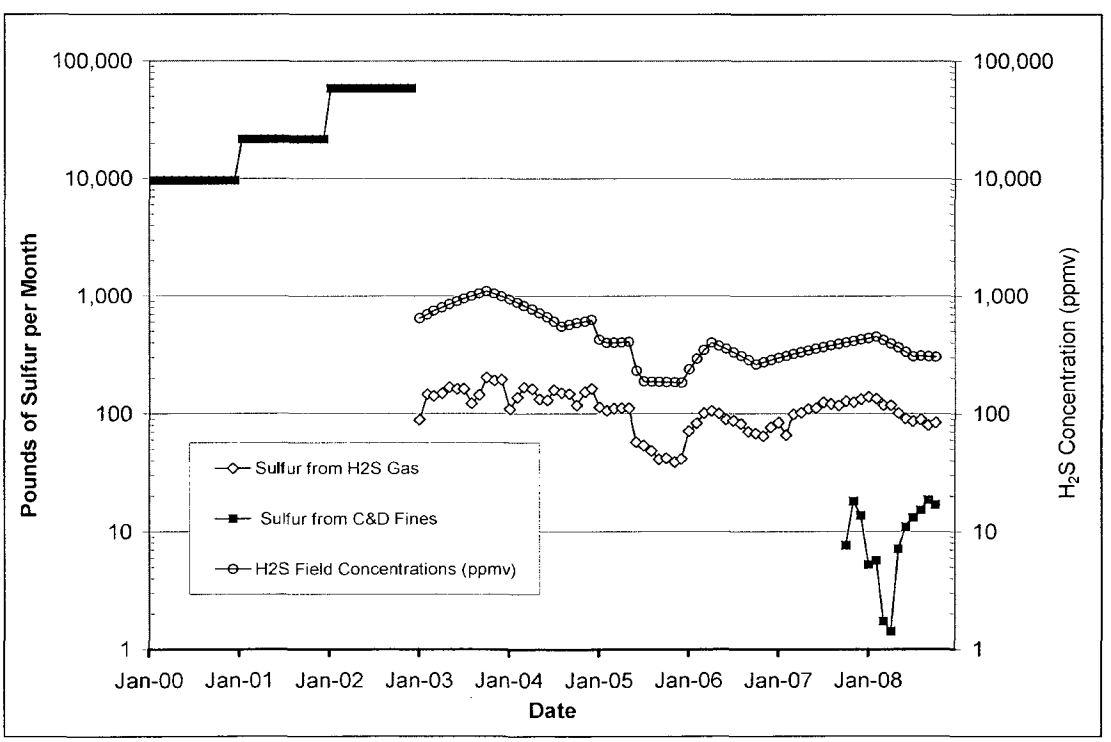


Figure 4.5 Comparison of Input of Sulfur from C&D Fines with H_2S Concentration in Landfill Gas at Site 2 Landfill

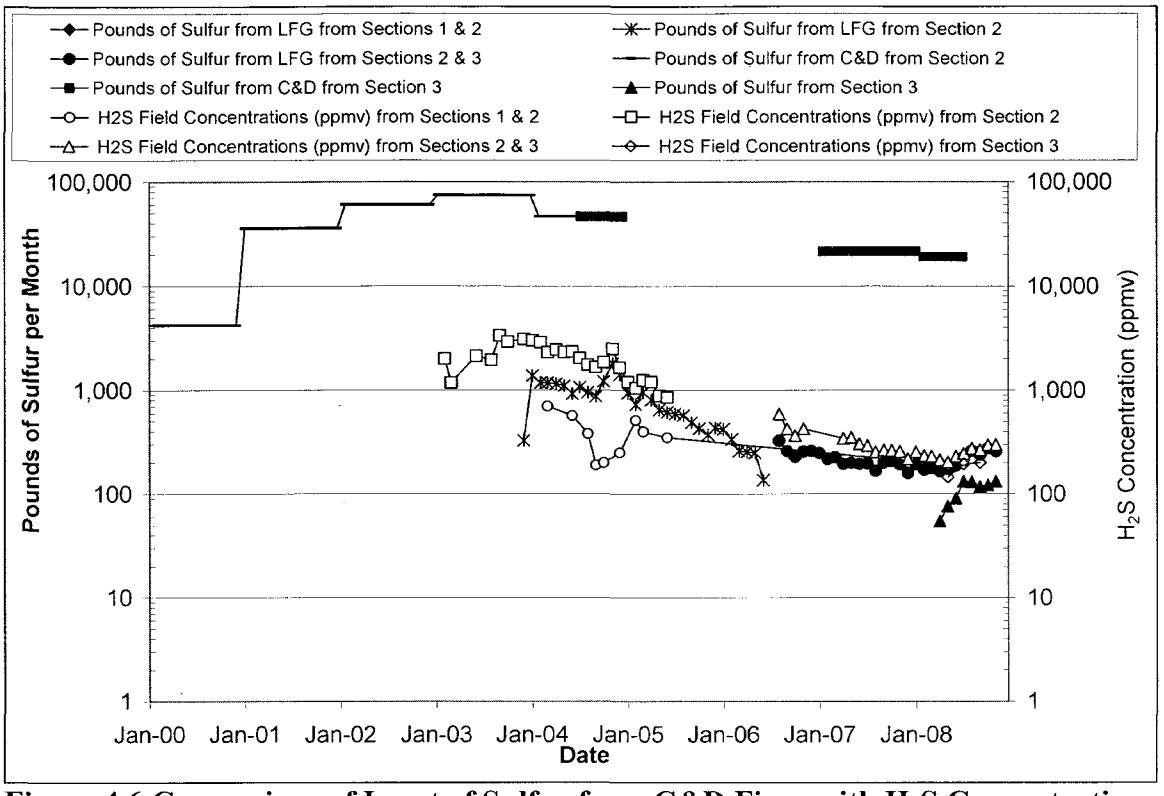


Figure 4.6 Comparison of Input of Sulfur from C&D Fines with H_2S Concentration in Landfill Gas at Site 3 Landfill

The lag in H_2S production from C&D debris is also noticeable in the Site 3 Landfill, as can be seen in Figure 4.6. This landfill is divided into three sections, and each of these sections accepted C&D waste over different time periods. The data available suggests that C&D fines were placed in section 2 from January 2000 through August 2004, C&D fines were placed in section 3 from July 2004 through June 2008, and no data was available for section 1. Likewise, H_2S data was collected from collection points that cover different sections of the landfill, as indicated in Figure 4.6. The highest concentrations of H_2S occur in section 2, where the greatest amount of sulfur from C&D fines was disposed of. The collection points where landfill gas from section 1 and 2 as well as section 2 and 3 did not achieve H_2S concentrations greater than 800 ppm. This

agrees with the conjecture that the amount of C&D fines and disposed of in a landfill is proportional to the amount of H_2S produced.

Table 4.6 compares the sulfur produced from C&D fines with the sulfur produced from the H_2S in landfill gas at the three landfills studied. The sulfur from C&D fines and residuals is the weighted total of C&D fines at each, and this was found by multiplying the total amount of C&D fines and residuals by the percent sulfur, which was in the form of sulfate. The sulfur from the H_2S in LFG was found by taking the amount of landfill gas produced and multiplying it by the percent H_2S. This value was then converted to a weight by the specific weight of H_2S. It appears that the amount of sulfur produced in the form of H_2S is one percent or less of the amount of sulfur placed in the landfills in the C&D fines. Other sulfate may exist in the landfill as well from sources such as sewerage, thus the actual amount of sulfur input into the landfill may be larger than the values listed in Table 4.6.

Table 4.6 Percent Sulfur in H_2S from C&D Fines

Location	Sulfur from C&D Fines and Residuals (lb)	Sulfur from H_2S in LFG (lb)	Percent Sulfur as H_2S
Site 1	22,821,315	41,465	0.18%
Site 2	1,077,501	7,824	0.73%
Site 3	3,118,103	31,079	1.00%

4.3.4. Moisture Content/LOI

Table 4.7, contains the results of the loss on ignition (LOI) procedure. This test describes the moisture content, organic carbon, inorganic carbon and the total loss on ignition of the C&D fines. All of the fines sampled, except CA_1, have a moisture

content in the range of 14 to 15%. These results are significant because moisture content is important in the reduction of sulfate to H_2S (Postgate, 1984). When the gypsum drywall in the C&D fines become wet, sulfate solubilizes and the sulfate reducing bacteria can use this sulfate as a terminal electron acceptor to produce H_2S (Yang et al, 2006). In addition to this, if the C&D fines are landfilled, there should be enough moisture provided by rain infiltrating the landfill as well. Additional moisture can also be provided when leachate recirculation is performed in order to increase methane production.

Table 4.7 Moisture Content, Inorganic and Organic Carbon Contents of Analyzed C&D Fines

Location	Moisture	Organic Carbon	Inorganic Carbon	Loss on Ignition (LOI)
MA_2	14.7%	16.7%	0.9%	32.4%
CA_1	9.1%	7.6%	12.6%	29.3%
CA_2	15.0%	11.7%	1.7%	28.4%
OR_1	14.0%	9.4%	2.2%	25.5%

The organic carbon that is present in the fines range from 7.6% to 16.7%. Organic carbon is a requirement of sulfate reduction and the organic carbon present in the fines is likely due to the presence of wood and paper, which are common in C&D fines (Yang et al, 2006). However, because these fines are utilized in an MSW landfill, there would be a sufficient amount of organic carbon in the MSW waste for the sulfate reducing bacteria to use. Therefore, it is unlikely that MA_2 fines (which contain the maximum amount of organic carbon) would have a tendency to produce a greater amount of H_2S if landfilled. Finally, inorganic carbon ranges from less than 1% to over 12%. This is the carbonate material that is liberated as CO_2 if the sample is heated to a temperature of at least 850°C (Dean, 1974).

Lastly, the total LOI is also shown in Table 4.3.4.1. The samples all had an LOI of between 25% and 33%. These values show the total mass of the moisture, organic and inorganic carbon of a sample produced by heating to a value of about 1000°C (Dean, 1974). These values are significant depending on what kind of industry in which the sample is used. The LOI procedure is used in the cement industry, where the LOI would be used to determine the amount of mass lost if the cement material were to be heated in a kiln. Likewise, it is used by combustion engineers to see what amount of mass would be lost if a sample was heated to a temperature of 950°C (ASTM D121-09).

4.4. Investigation of Hydrogen Sulfide Production from Exhausted Materials

4.4.1. Overview

The following section shows the results of an experiment to see if hydrogen sulfide (H_2S) can be produced from materials that have already attenuated H_2S. As mentioned in the previous chapter, the different materials include the four ashes used for the ex-situ landfill gas experiment, sulfur cake and paper made with zeolite that has been used for H_2S removal. These materials have been put into an anaerobic environment (simulated landfill) and monitored for several parameters. The results of the parameters measured are included in this section.

4.4.2. pH of Experimental Columns

The pH of the different samples as well as the pH of the RO water and leachate added to the samples can be seen in Figure 4.7. Recall that the pH of the leachate of the different ashes ranged from 6.36 to 11.67. However, in this experiment, the pH seems to

be completely dependent on the pH of the RO water added or the leachate added. As previously stated, the RO water was added for the first 53 days of the experiment, and leachate from a closed landfill was added to replace the leachate removed from the columns. It appears that the leachate from the columns is between about 5.5 and 7 with the addition of RO water. When leachate was added to the columns the pH was slightly higher, mostly between 7 and 8.

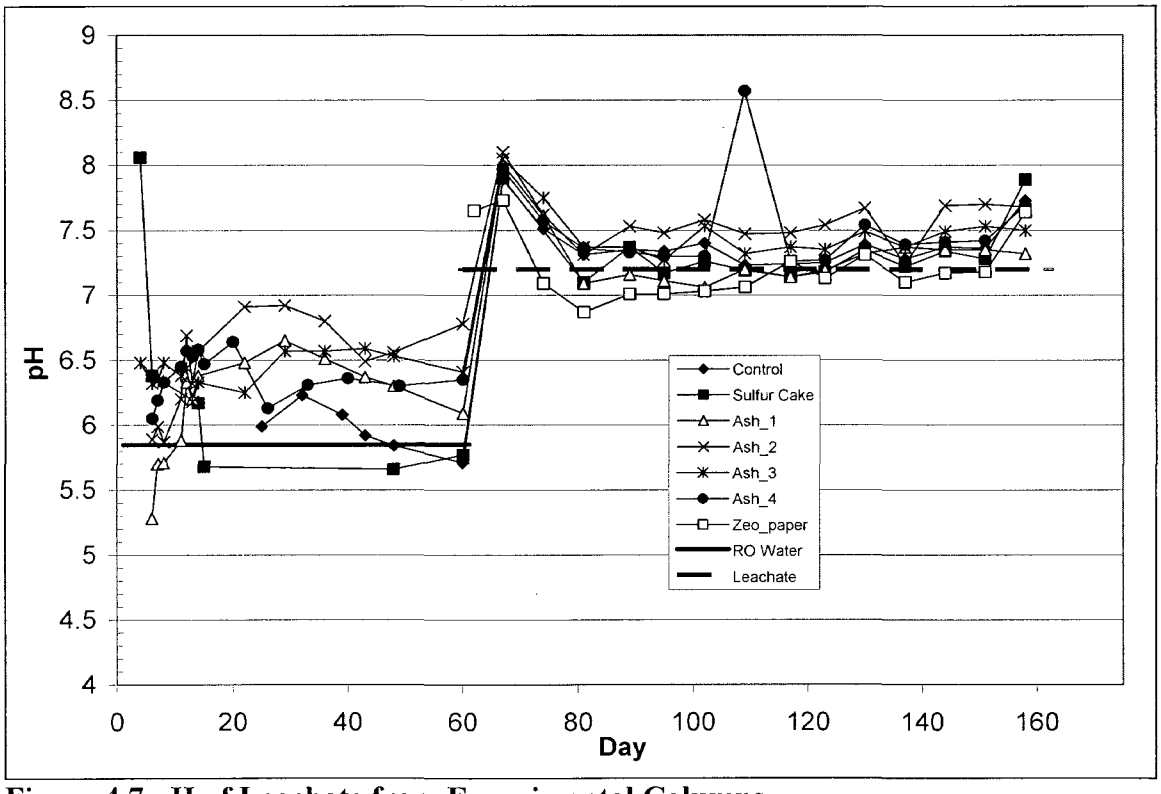


Figure 4.7 pH of Leachate from Experimental Columns

As mentioned in the previous section, the pH of the different samples was measured periodically throughout the experiment. According to Postgate, most SRB tolerate a pH in the range of 5 to 9.5 (Postgate, 1984). Therefore, it seems that all the

column environments would be able to sustain SRB which could reduce sulfate to H_2S, when considering pH only.

The form and amount of sulfur that exists in each column is not known, except the column containing sulfur cake, which can be estimated. This column contains approximately 4.4g of sulfur since there is 5g sulfur cake at about 87% sulfur (see Chapter 2). As previously discussed, is suspected that the form of sulfur that exists in each sample prior to biological activity is sulfide (S^{2-}). Because the pH is low, the species of sulfur that exists will most likely be in the form of dissolved HS^- ions and H_2S as the pK_a's are about 7 and 13 (Benjamin, 2002). Therefore, if sulfur in the form of sulfide has formed on the samples when the ash was tested to see if it could attenuate H_2S, it may have the potential to produce H_2S in liquid or gaseous form.

4.4.3. Oxidation Reduction Potential of Experimental Columns

The oxidation reduction potential (ORP) of the leachate from all samples as well as the RO water and leachate is shown in Figure 4.8. As can be seen from this figure, the RO water had an ORP of about 100 mV whereas the leachate added was about -68 mV. Generally, the ORP was higher when the RO water was added to the columns and when the leachate was added, the ORP decreased to more negative values. It is also clear on Figure 4.8 that the ORP was low towards the beginning of the experiment. This low ORP at the beginning may be due to a large amount of microbial activity creating a reducing environment that was present in the columns.

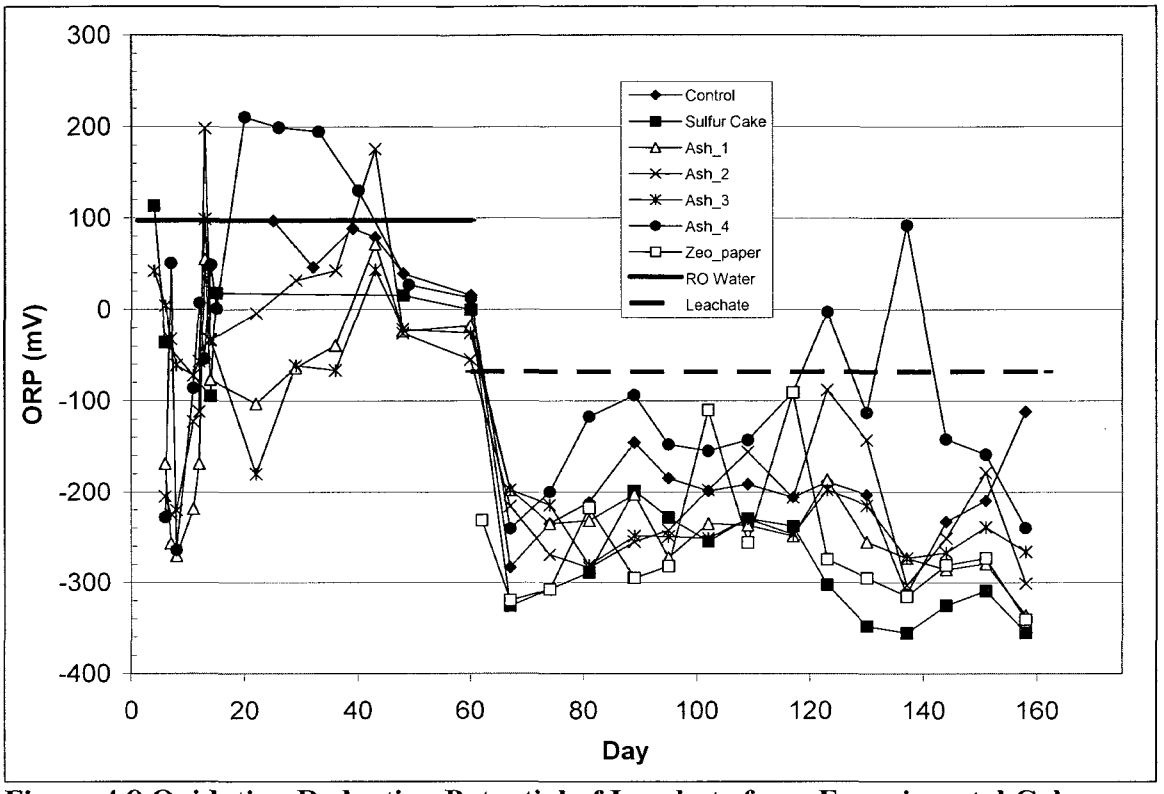


Figure 4.8 Oxidation Reduction Potential of Leachate from Experimental Columns

While not always a reliable measurement, ORP is an indication of a reducing or oxidizing environment, with a more negative ORP being more reducing and a positive ORP indicates an oxidizing environment. According to Postgate, the oxidation-reduction (redox) potential of the environment in which SRB conduct their metabolic functions most efficiently is below -150 to -200 mV (Postgate, 1984). Therefore, it is likely that after the introduction of leachate from the landfill, the SRB will tend to produce a greater amount of H_2S because ORP of the leachate was much lower than that of the RO water.

There is a high amount of variability in measuring the ORP of the leachate of the columns. One reason that may account for this is the exposure to oxygen in removing the leachate from the column and reading the ORP with the YSI probe. The ORP value will likely increase if the column is exposed to oxygen. Likewise, if any of the experimental

columns is not completely sealed, oxygen may infiltrate, increasing the ORP. This did not appear to be a significant issue in any of the columns; however, it is virtually impossible to ensure an entirely anaerobic condition for all columns.

4.4.4. Dissolved Oxygen Concentration of Experimental Columns

The concentration of dissolved oxygen (DO) in the leachate in each column is shown in Figure 4.9. The RO water, which was added to the columns from the beginning of the experiment until day 53, had a DO concentration of almost nine, whereas the leachate which was added after the RO water had a DO concentration of less than one. As one would suspect, the DO of the columns generally decreased once the leachate was added.

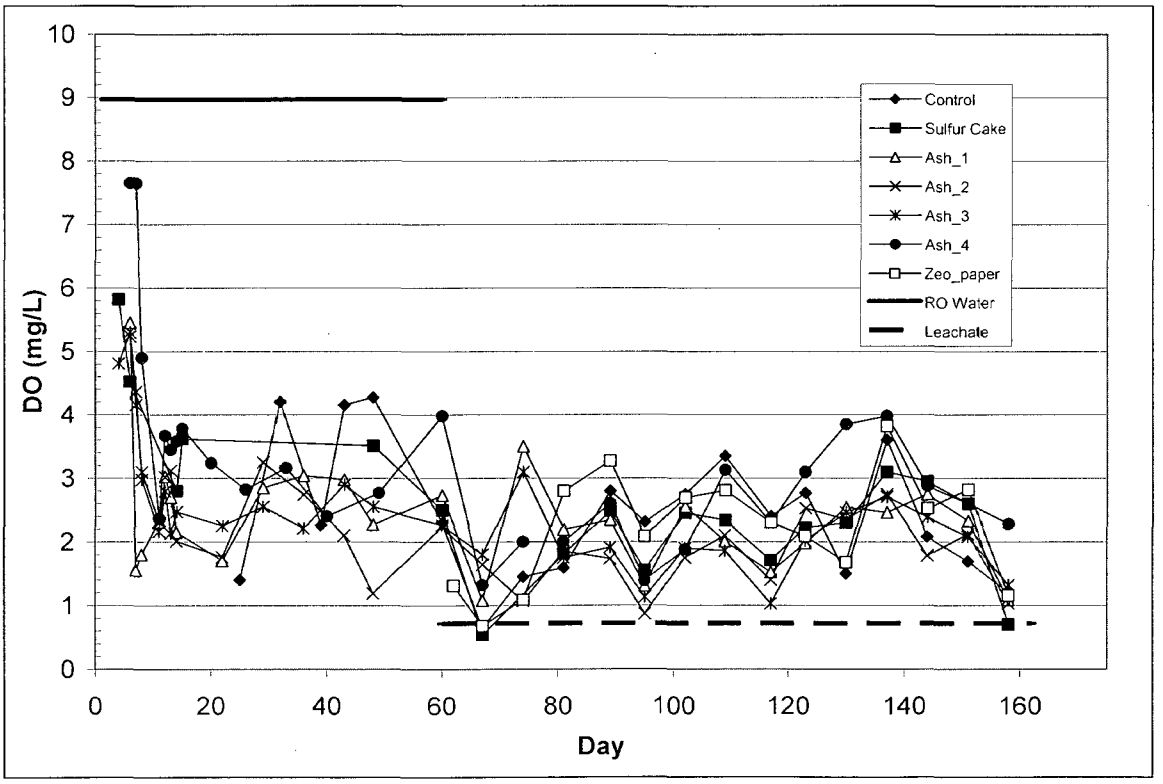


Figure 4.9 Dissolved Oxygen of Leachate from Experimental Columns

The DO, as well the ORP, of the leachate of the columns is an indication of the reducing conditions of the leachate (Jang and Townsend, 2003). The closer to zero, the more reducing the environment is. So, because the columns studied were maintained to be anaerobic, or without oxygen, a lower DO (less than one) was expected. The DO may not have achieved this value because the experimental column was not 100% sealed. Further, when the DO is analyzed the leachate comes in contact with the air, which will increase the DO. The DO of the leachate may not be an exact reflection of what type of an environment each area of the column is. Because the DO is not zero, there may be areas in which air exists in the column. However, there may also be pockets of the column in which there is no air and the SRB can reduce the sulfate to produce H_2S.

4.4.5. Sulfide Concentration and Sulfide Relationships of Experimental Columns

The sulfide measurements from the leachate for the columns can be seen in Figure 4.10. There was a dramatic increase in sulfide concentrations in all columns once the leachate from a closed landfill cell was added on the 60^{th} day of the experiment. Before this, sulfide concentrations generally were below 1 mg/L, whereas after the addition of leachate, sulfide concentrations in some columns were above 30 mg/L. Even though the sulfide concentration of the leachate added to the columns was 0.16 mg/L, the sulfide concentrations may have increased due to the SRBs that exist in the landfill leachate.

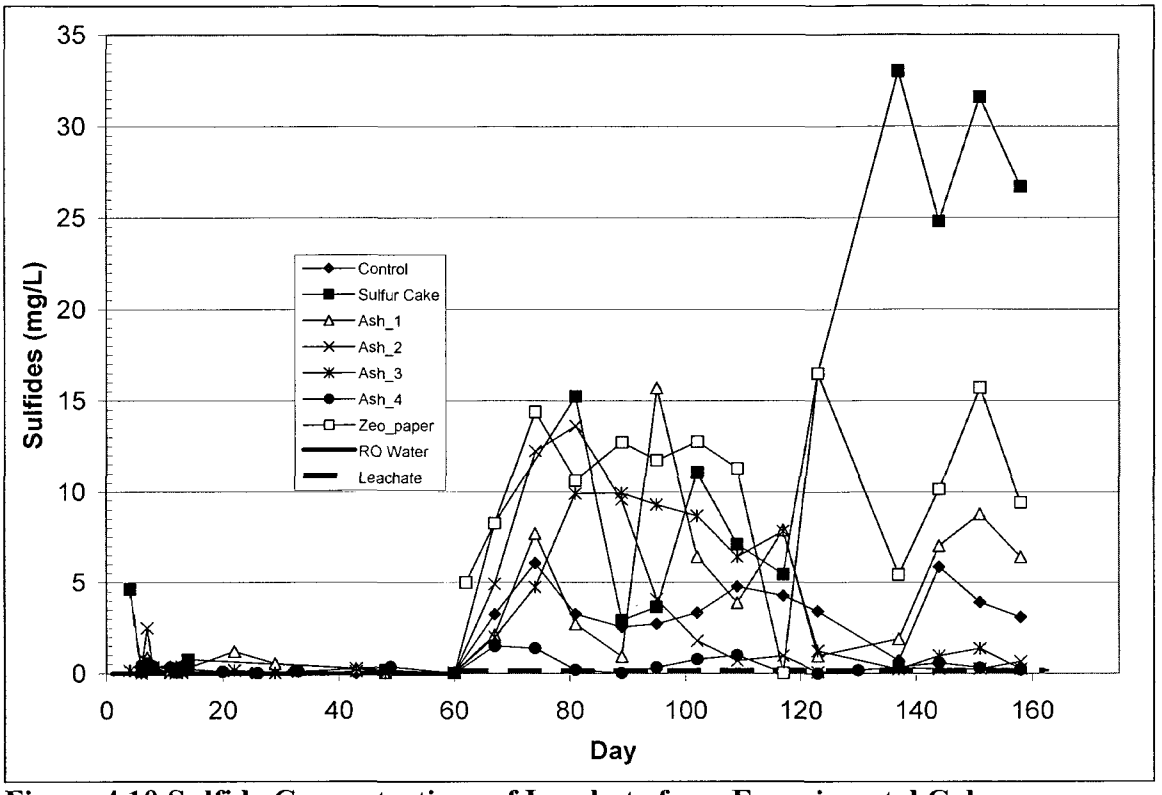


Figure 4.10 Sulfide Concentrations of Leachate from Experimental Columns

The sulfide concentrations can be in the form of total sulfides, H_2S, HS^-, or metal sulfides (HACH Method 8131). Therefore, the exact form of the sulfides is unknown, but there can be speculation based upon the pH and ORP. From Figure 4.10, it appears that the highest sulfide concentrations exist at a pH of about 7. This neutral pH exists in the aforementioned range in which SRB have the potential to reduce the most sulfur. Because the first dissociation constant is about 7, it is likely that sulfur exists in nearly equal forms of H_2S and HS^-. Nearly no sulfides exist when the pH is below 7. This lack of sulfides may be due to the fact that RO water was added to the experimental columns and generally produced a pH of less than 7 (Figure 4.11). So, although it has been shown in previous research that the sulfide concentration is directly related to pH (Connell and Patrick, 1968); in this experiment, the sulfide concentration may have been

more dependent on whether RO water or leachate water was added to the experimental columns.

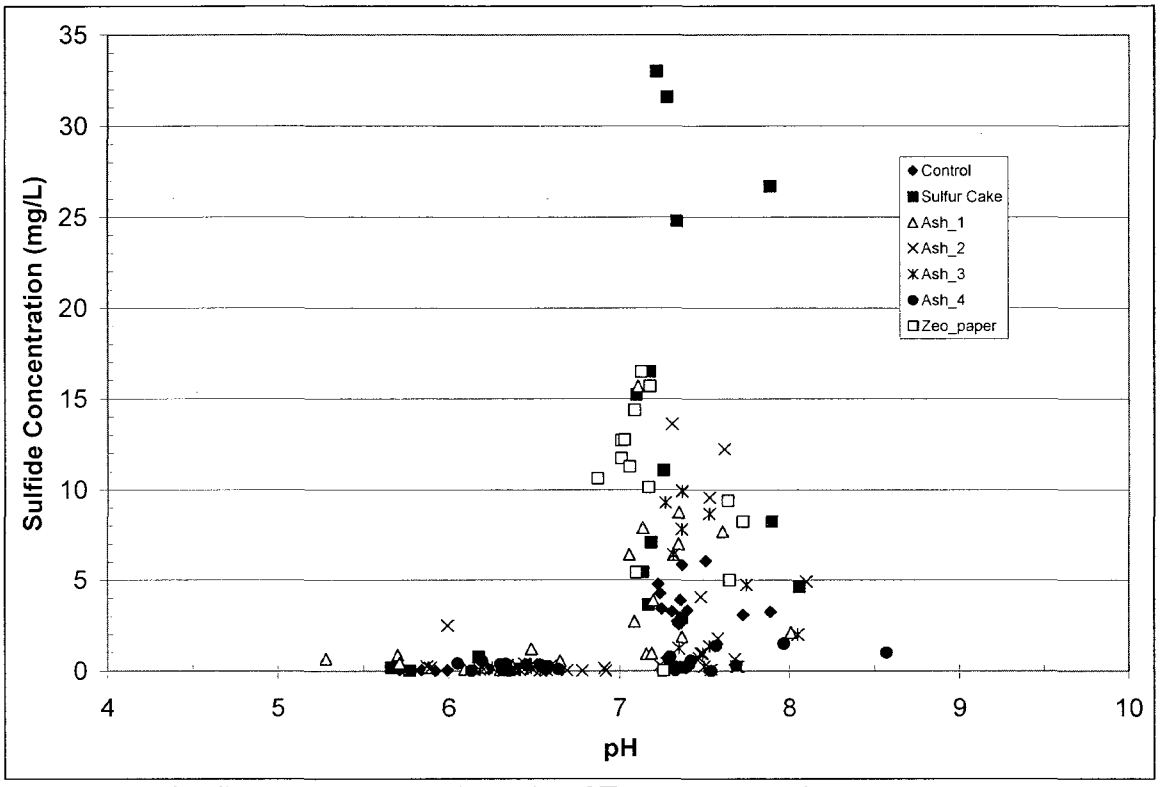


Figure 4.11 Sulfide and pH Relationship of Experimental Columns

Likewise, there appears to be a relationship between the sulfide concentration and the ORP of the leachate from the columns. The higher sulfide concentrations generally occur at an ORP approaching -300mV (Figure 4.12). The columns containing sulfur cake, zeolite paper, Ash 1 and Ash 2 displayed high sulfide concentrations and had a more negative ORP. Again, it is noted that with an ORP below -200 mV, it is more likely that the SRB are active (Postgate, 1984). Because of this, the sulfide, especially at this ORP, will be in the form of H_2S (Connell and Patrick, 1968). At a neutral pH, which

is close to what most of the data is, The other columns may not have high sulfides in them for several reasons. Perhaps the sulfur is in another form such as sulfate.

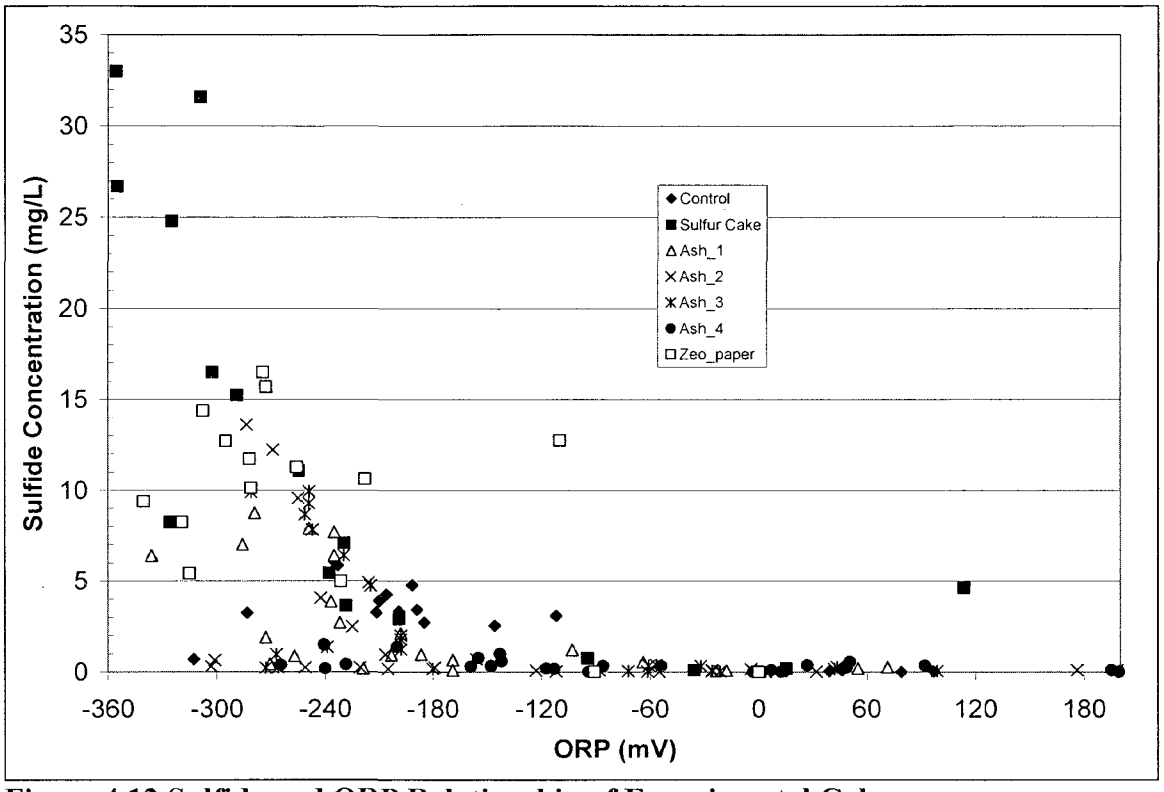


Figure 4.12 Sulfide and ORP Relationship of Experimental Columns

4.4.6. Hydrogen Sulfide Concentrations of Experimental Columns

The purpose of this experiment is to see if H_2S can be produced from materials that have previously attenuated H_2S and are put back into an environment that would be conducive to sulfur reduction. Although these columns contained varying amounts of sulfur, it appears that the amount of sulfur lost in the form of sulfides in the leachate and H_2S gas from the column was not rate limiting. Less than 22 % of the sulfur was lost in the column containing ZeoBloc ™. The other columns had a loss of less than 10%.

Figure 4.13 shows the H_2S concentrations from the different columns. Because the graph is plotted on a logarithmic scale and several of the samples were at 0.000 ppm H_2S, they were plotted as 0.001 ppm, since the JEROME has an error of +/- 0.003 at this of a concentration. Although most of the readings were low, mostly less than 1 ppm, the column containing sulfur cake on had a concentration of 50ppm, 190ppm and on the last day of the experiment had a concentration of 640ppm. The concentrations of H_2S, however, generally did increase with the addition of leachate from the landfill that began midway through the experiment. There may be a greater number of SRB in this leachate, which indicates that a greater amount of H_2S can be produced. However, even though the concentrations of H_2S may be low at this time, it does not mean that these materials will not regenerate H_2S.

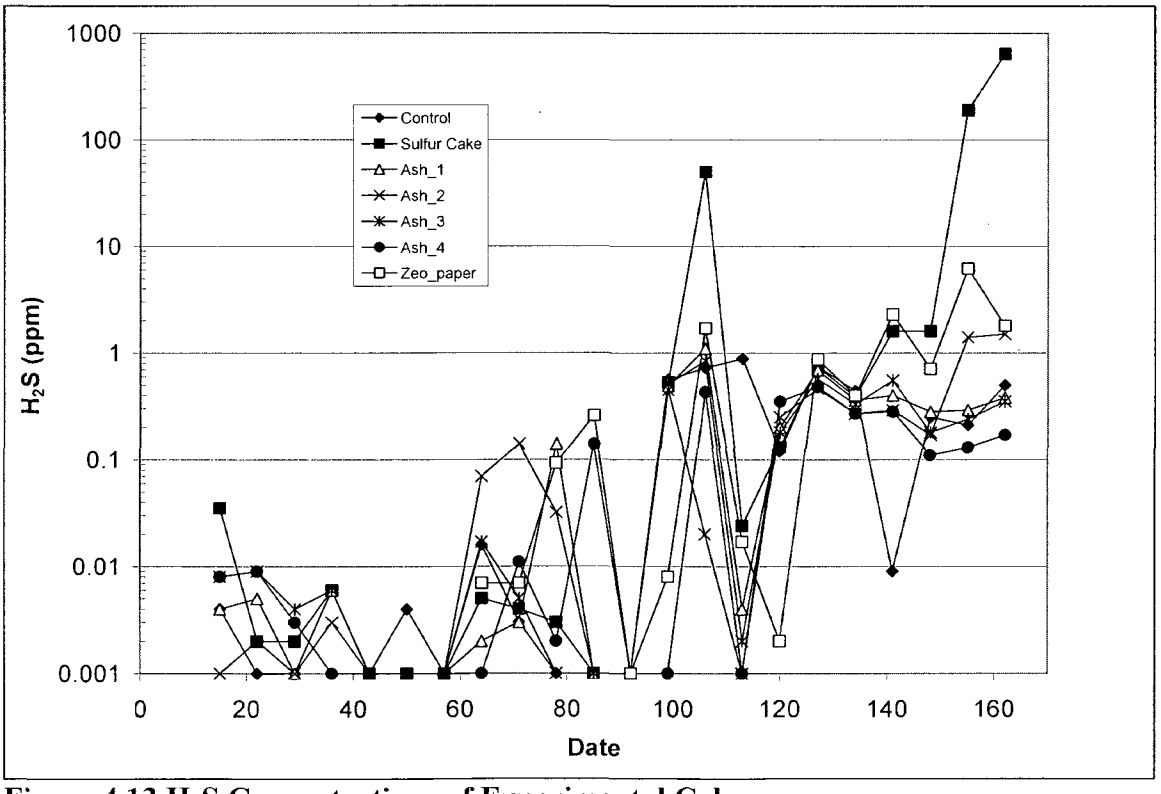


Figure 4.13 H_2S Concentrations of Experimental Columns

While the H_2S concentrations were relatively low, there were differences between some of the experimental columns. As mentioned, the column containing sulfur cake on several occasions produced high concentrations of H_2S. This column also had high concentrations of sulfides, and this can be seen further which can be seen in Appendix C. Assuming the sulfur present in the sulfur cake was elemental sulfur with an oxidation state of zero; the sulfur could have been reduced to an oxidation state of -2 due to the bacteria that may have been present, pH and ORP. In the other columns, the H_2S values may have been low for several reasons. As stated earlier, with a higher than normal DO, oxygen intrusion may have hindered the production of H_2S, as sulfur reduction occurs in a reducing environment. In addition, the H_2S readings are taken only from one section of the column. This area of the column is not necessarily indicative of what kind of gases may be present in the entire column.

4.5. Examination of Materials Used for Hydrogen Sulfide Inhibition

4.5.1. Overview

This section contains the results of an experiment in which different materials were mixed with construction and demolition (C&D) debris fines to determine if they have the potential to inhibit the production of hydrogen sulfide (H_2S). The materials investigated in this experiment were lime ($(CaOH)_2$), quicklime (CaO), unused Ash 1 from the ex-situ landfill gas experiment, and a zeolite powder. Like the experiment

discussed previously, the same parameters (pH, ORP, DO, etc) were recorded to evaluate column and material performance.

4.5.2. pH of Experimental Columns

The pH of leachate from the different columns is presented in Figure 4.14. It is clear there is a disparity between the pH of the leachate of the columns which contained lime or quicklime and the rest of the columns. As previously mentioned, the pH of lime and quicklime is above 12. In the columns that contain these materials, the pH generally remains near this level. The other columns remain relatively neutral throughout the experiment. The exception to this is on day 109, when the pH of the columns did not follow the trend. All of the columns were approximately 10, except the columns containing Ash 1 and Zeobloc. Therefore, it is likely that there was either an error in sampling or the YSI probe, which read pH, was not working properly.

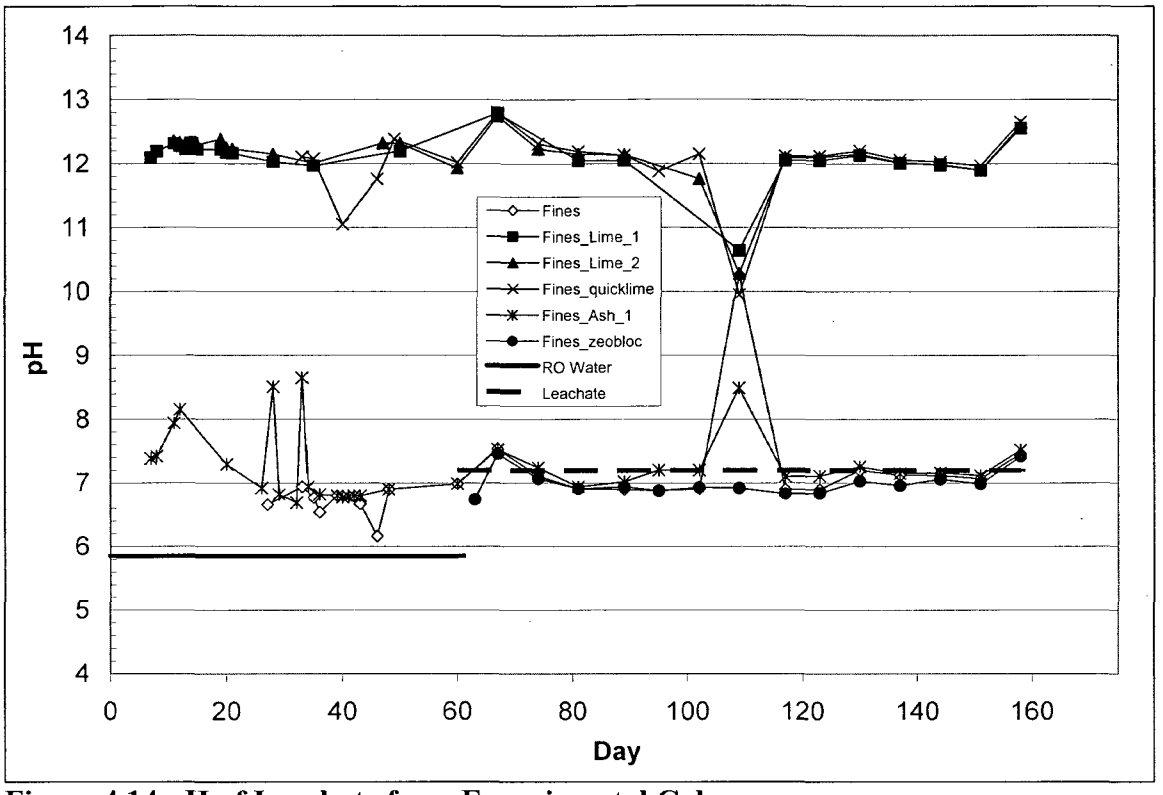


Figure 4.14 pH of Leachate from Experimental Columns

The sulfate present in the C&D fines, which all these columns contain, will have the tendency to reduce to H_2S if placed in an anaerobic environment and have a carbon source such as the paper which C&D is known to contain. The pH of the environment is also an important parameter of sulfate reduction. As mentioned earlier, the pH of SRB needs to be relatively neutral in order to most efficiently reduce the sulfate. Thus, a pH of about 12 is not conducive to sulfate reduction. At this pH, the sulfur more likely will be in the S^{2-} or SO_4^- (Appendix F). However, high H_2S concentrations can still occur in these columns because the high pH does not necessarily occur throughout the entire experimental column. It was assumed that in those columns containing lime or quicklime in addition to the C&D fines, the contents were completely mixed. This is not necessarily entirely true because pockets may exist in which the lime or quicklime may

not be in contact with the C&D fines and the carbon source. Because of this, H_2S can be produced in these regions and detected by the JEROME meter when sampling.

4.5.3. Oxidation Reduction Potential of Experimental Columns

The oxidation reduction potential (ORP) readings from the leachate from the columns is presented in Figure 4.15. Negative ORP values can be seen in the first two weeks of the experiment. Like the previous experiment, this drop in ORP may be due to a ratio of RO water to solids in the experimental column in which SRB work best, as less RO water has been added than later in the experiment. Also, with the addition of leachate from the landfill, the ORP values of the leachate from the columns all became more negative. This may indicate that a more reducing environment is present. Again, SRB work best in an environment with an ORP below -200 mV. Such a low ORP was achieved only on day 109 and day 158 of the experiment for both columns containing C&D fines and lime as well as the column containing the C&D fines only.

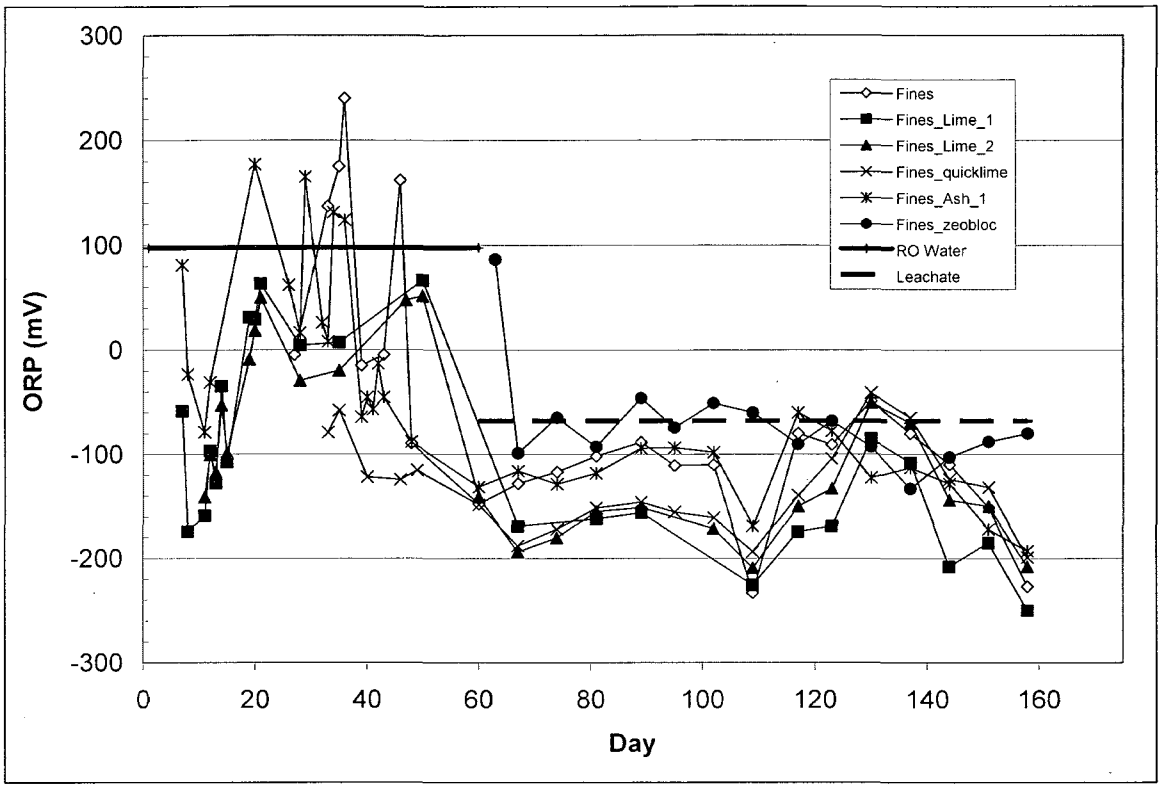


Figure 4.15 Oxidation Reduction Potential of Leachate from Experimental Columns

According to Postgate, sulfate reduction can only occur at a redox potential below -150 mV (Postgate, 1984). Several of these columns contained leachate at or above this threshold during the first part of the experiment, which may indicate the low H_2S concentrations. However, it is important to note that the ORP values from the leachate collected from the columns may read slightly higher than the actual ORP. This is because the leachate comes into contact with the air between when it exits the column and is measured, and this may increase the ORP.

4.5.4. Dissolved Oxygen Concentrations of Experimental Columns

The dissolved oxygen (DO) concentration of the leachate of the different columns is presented in Figure 4.16. The DO of the leachate remained lower than the RO water, which was added during the first few weeks of the experiment. This may indicate that a

more reducing environment was present. However, even with the addition of leachate from the closed cell of a landfill, with a DO concentration of less than 1 mg/L, was added, there was no decrease in the column leachate DO. In fact most of the columns showed an increase in DO concentration.

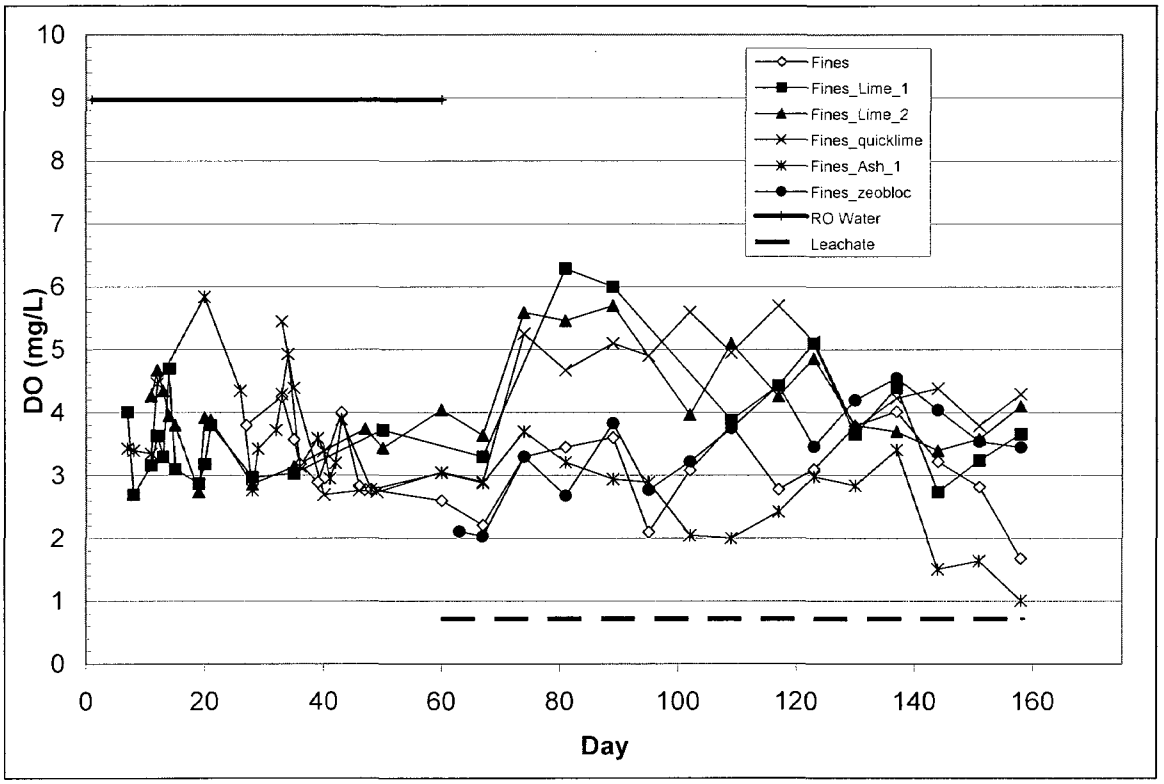


Figure 4.16 Dissolved Oxygen of Leachate from Experimental Columns

As previously mentioned, these columns are designed to be anaerobic, but this condition is not met. The aerobic environment of the experimental columns should change quickly as the columns are to be sealed and thus oxygen not permitted to enter the columns. However, all columns, except the column containing the C&D fines and Ash 1 never had consecutive readings below 2 mg/L. Again, these high DO values may be due to leaks in the columns and the leachate from the experimental columns coming in

contact with the air before the values are read. Because of potential leaks in the column, the H_2S values may not have been as high as they had the potential to be.

The DO values may also have been higher than expected in the columns containing the lime and quicklime due to the presence of oxygen. If the OH^- or O^{2-} dissociates then more oxygen is present and the pH will increase. As can be seen from Figure .17, the DO of the columns containing lime and quicklime never dropped below 2 mg/L and generally stayed above 3 mg/L.

4.5.5. Sulfide Concentration and Sulfide Relationships of Experimental Columns

The sulfide concentrations from the H_2S inhibition experiment columns can be seen in Figure 4.18. Sulfide concentrations were generally below 0.2mg/L until about six weeks into the experiment, when the concentrations increased slightly. The column that experienced the greatest concentrations of sulfides was the column containing the first C&D fines and lime column. The leachate from this column had sulfide values of above 1.5 mg/L on three occasions. The next highest sulfide concentration was 1.025 mg/L, and this was from the column containing the C&D fines only. These values are much lower than the sulfide values obtained in the previous experiment. The reason for this may be due to the fact that C&D fines contain sulfur in the form sulfate, whereas in the previous experiment, it is suspected that sulfur is present in the elemental sulfur form. When the pH is neutral or greater and the ORP is above -200 mV, sulfur is more likely to be in the sulfate form instead of the sulfide form, according to thermodynamic tendencies

of sulfur species. Therefore, it appears that the SRB are not as active as in the previous experiment.

Sulfide is the end product of sulfate reduction (Postgate, 1984). Since the average sulfate content of C&D fines was found to be almost six percent, one would expect higher concentrations of sulfide in the leachate. One reason that the sulfide concentrations of the experimental columns were so low is that the sulfate is not being efficiently reduced to sulfide. In columns that contain lime and quicklime, the pH was near 12, which negatively affects sulfate reduction (Figure 4.18). As mentioned, the ORP of the leachate from the columns generally did not go lower than -200 mV except on day 144 and 158, and the DO did not go below 1 mg/L. These conditions may indicate that the SRB did not have a suitable environment for sulfate reduction.

However, the columns that contained lime, quicklime, Ash 1 and Zeobloc were suspected to inhibit the production of H_2S. The SRB would be less active in these columns and because of this, the sulfide concentration would be lower then the control (C&D fines only) column. Despite this, these experimental columns did not produce leachate that contained a substantial amount of sulfides. Again, this may be due intrusion of oxygen when the column was sampled or because the column may not be sealed effectively.

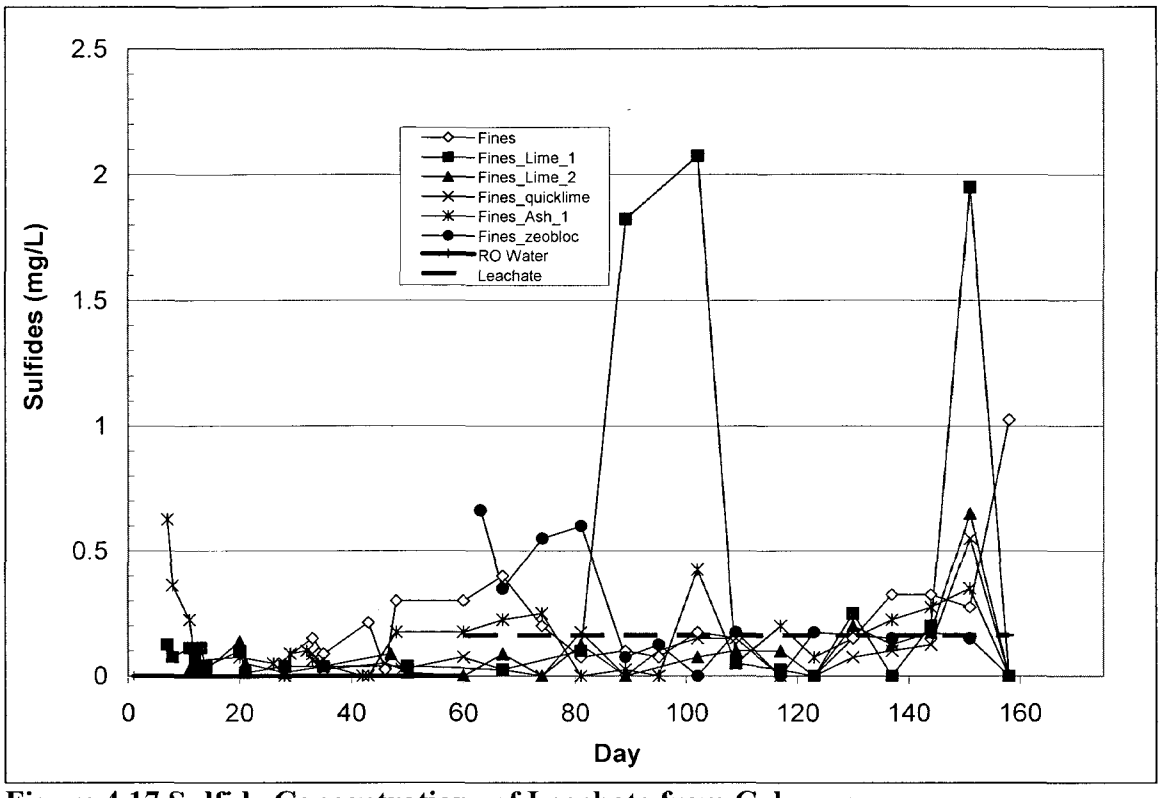


Figure 4.17 Sulfide Concentrations of Leachate from Columns

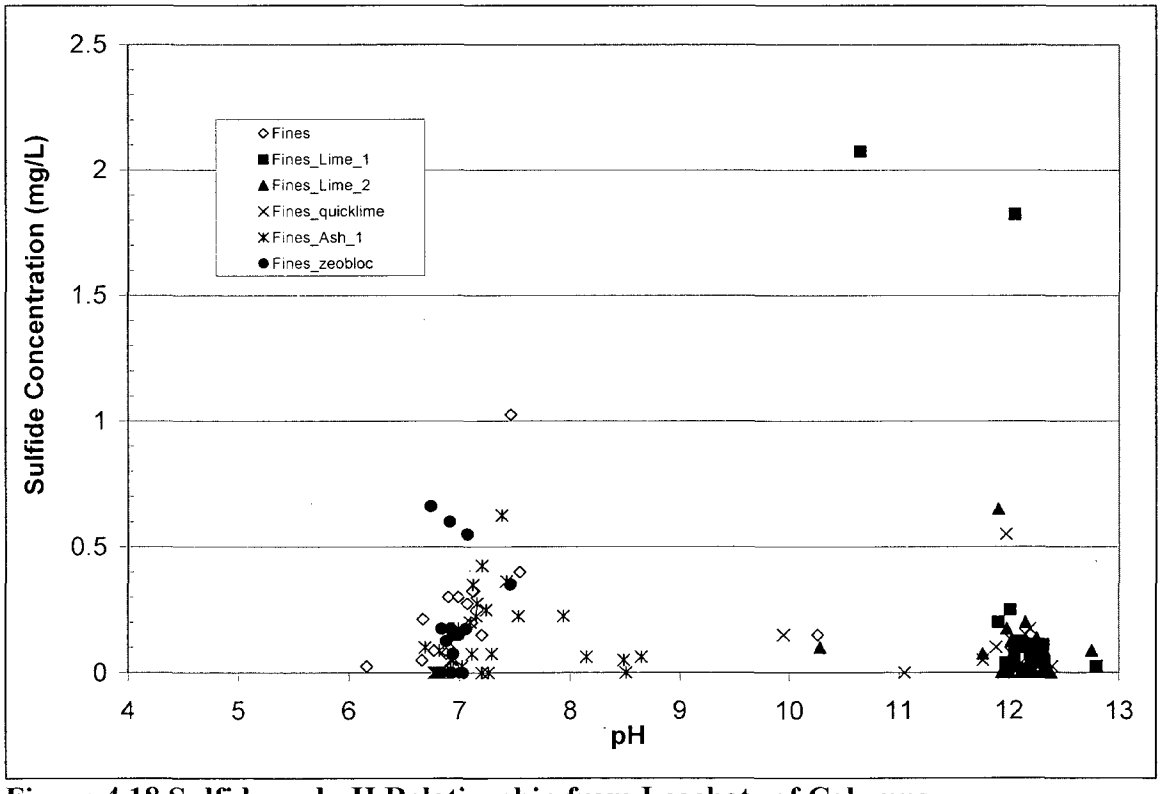


Figure 4.18 Sulfide and pH Relationship from Leachate of Columns

There does not seem to be as strong a correlation between the sulfides present in the leachate and the ORP of the leachate, as can be seen in Figure 4.19. Generally, there were no sulfide concentrations above 2 mg/L except with one reading of the columns containing C&D fines and quicklime. When this sample was taken, there was insufficient leachate to sample the ORP, so the corresponding ORP of this sample is unknown. However, the general trend of this graph comparing ORP and sulfide indicates higher sulfide readings closer to about -175 mV for the columns containing only the C&D fines and the C&D fines with Ash 1. No similar or other apparent trend existed for the other columns.

As previously stated, ORP is measured because it is can indicate to what degree the environment is reducing or oxidizing. Sulfides are measured, and as can be seen from the results of the previously described experiment, the sulfide concentration of the leachate is generally higher at a more negative ORP. The results of this experiment indicate that SRB are more active in reducing sulfate, which is present in the C&D fines, to sulfide at an ORP of about -175mV. Also, the ORP of the columns was never recorded at a value below -250 mV, except on day 158 where the column containing the C&D fines and lime had an ORP of -250 mV. Thermodynamically, the ORP needs to be below about -200 mV at a neutral pH and even lower if the pH is higher in order for the sulfur to be in the reduced sulfide form. Therefore, the ORP indicates that the SRB were not as active as in the previous experiment.

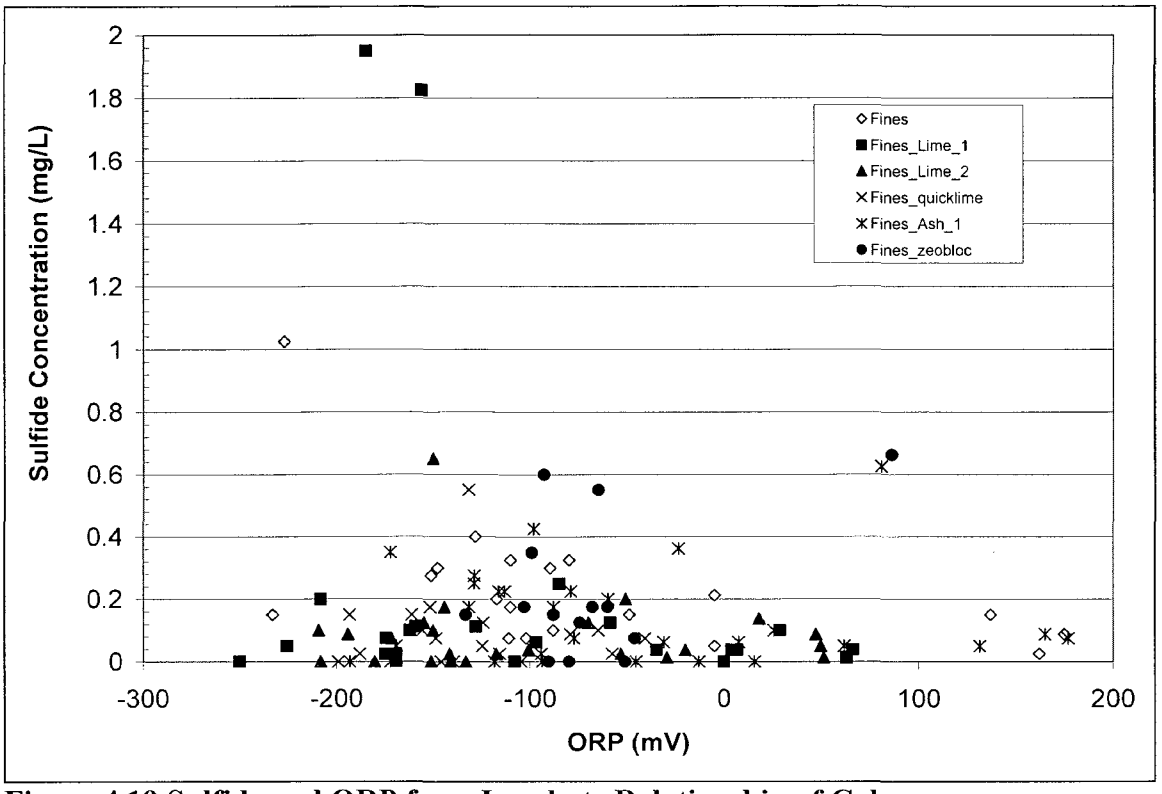


Figure 4.19 Sulfide and ORP from Leachate Relationship of Columns

4.5.6. Hydrogen Sulfide Concentrations of Experimental Columns

Like the previous experiment, H_2S readings were taken weekly. Similar to the previous experiment, the sulfur lost in the form of sulfides in the leachate and H_2S gas was determined to see if it was rate limiting. The columns in this experiment have lost less than 0.003% of sulfur in these forms, and therefore the sulfur loss is assumed not to be rate limiting. However, because the columns in this experiment contain C&D fines, it is assumed that significant amounts of sulfur may be present in the form of sulfate. This sulfate present may have dissolved in the leachate of these columns and been removed.

As can be seen in Figure 4.20, all columns showed little H_2S production when RO water was added (until day 53). Beginning on day 99 of the experiment, H_2S concentrations of 0.5ppm were recorded in the columns containing the C&D fines with

Ash 1 or the C&D fines with the Zeobloc. In addition, the maximum concentration of H_2S observed was 13ppm, which occurred with the column which is called Fines_Lime_2. This is not necessarily representative of the entire column because columns were only taken at a discrete point of the column.

Also, the H_2S concentrations increased with the addition of leachate from the closed section of a landfill, which was first added on day 60 of the experiment. It is clear that all the columns increased by at least an order of magnitude from where they were on day 60 of the experiment. The increase in H_2S concentration is not surprising because of the low DO and ORP of the leachate added to the columns. In addition, the increase in H_2S concentration later in the experiment may be due to more sulfate reducing bacteria that have been given the opportunity to grow in the experimental columns. As SRB are given more time in a column that contains little oxygen, it may give the bacteria more time to reproduce and thus produce more H_2S.

Still the concentrations of the different columns were generally low. This may be due to the size of the experimental columns. In previous similar experiments (Yang et al, 2006, Jambeck et al, 2008), the experimental columns were much larger. Therefore, the amount of carbon and number of bacteria has the opportunity to be greater. In addition, all the columns, except the column containing only C&D fines, had materials that have the potential to inhibit the production of H_2S. Therefore, these materials may be in fact stop the SRB to produce H_2S, while the column containing only C&D fines may have not produced the expected amount of H_2S.

A further reason that may have lead to the inhibition of SRB in the experimental columns is the sulfur to carbon ratio, This ratio is taken from the amount of sulfur in the

form of H_2S in landfill gas and was the average of those values attained in the first experiment. The total amount of carbon in the landfill gas was assumed to be from the CO_2 and CH_4, and these values were taken from the GEM readings, also in the first experiment. The average carbon to sulfur ratio found was about 333 to 1. Assuming that the same ratio existed in the experimental columns of the inhibition experiment, an inhibitory effect may have existed. The amount of sulfur present may need to be higher in order for the SRB to work most efficiently.

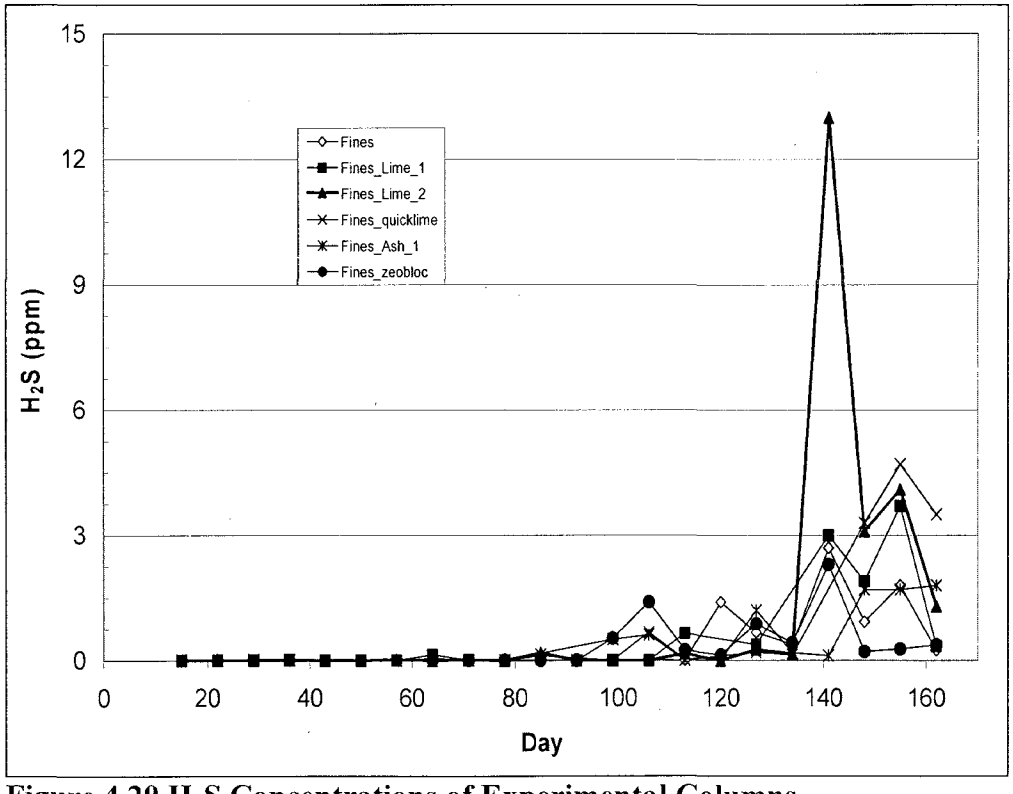


Figure 4.20 H_2S Concentrations of Experimental Columns

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Hydrogen sulfide (H_2S) has become accepted as a harmful and problematic gas emitted from landfills. As previously mentioned, this potentially dangerous gas can be produced from construction and demolition (C&D) debris, if landfilled. Therefore, this research consisted of examining alternative treatment of H_2S in landfill gas at landfills, a comparison of input sulfur inputs and outputs at landfills and generation/prevention of H_2S in the landfill setting. This research is composed of four different sections: an ex-situ landfill gas experiment to evaluate H_2S attenuation with industrial materials; C&D fines analysis; an in-situ landfill simulation to test H_2S prevention; and an in-situ landfill simulation experiment to evaluate H_2S generation.

The first experiment, the landfill gas ex-situ experiment, was designed to evaluate various ashes for attenuating hydrogen sulfide from landfill gas. Of the four different ashes tested, it appears that Ash 1 was able to attenuate the greatest amount of H_2S per mass of ash at 73.80 milligrams H_2S per gram of ash. Similarly, this ash was able to attenuate 26.57 milligram H_2S per cubic centimeter of ash. The mechanism of attenuation of H_2S is believed to be oxidation, but adsorption may have also accounted for some of the attenuation. Factors including pH of the environment, presence of water as well as surface area of the ashes may have contributed to the attenuation of H_2S. In

addition, metals such as iron(II), and metal oxides such as calcium oxides may have been responsible for the conversion of H_2S to a higher oxidation state of sulfur.

The use of ash may be a more favorable option for landfill operators to utilize because of its ability to preferentially attenuate H_2S in landfill gas (leaving methane still to be beneficially used). Also, because ash is a byproduct rather than the primary product, it may be less expensive than other H_2S scrubbing materials. In order to show that ash is a desirable alternative to other H_2S scrubbing systems, these ashes should be tested on a larger scale. The ash could be tested to treat the flowrate of an entire landfill gas well.

The second study involved the characterization of construction and demolition (C&D) fines for sulfate, moisture and carbon content. In addition, the input and output of sulfur in terms of sulfate from C&D debris fines and sulfur in landfill gas was presented. The sulfate content of C&D fines was determined because it is one of the sources of H_2S in the landfill setting. It was found that the range of sulfate content of the C&D fines from C&D processing facilities was1.6% to about 15.2%, with an average of 5.92%. In addition, the amount of sulfur output in the form of H_2S in landfill gas compared with the amount of sulfur input in the form of sulfate from C&D fines ranged from 0.18% to 1.00%.

The percent sulfate in C&D fines as well as the quantity of C&D fines is significant to landfill operators. A relationship exists between the sulfur input in the form of sulfate from the C&D fines and the amount of sulfur output in the form of H_2S in landfill gas. This relationship is important because H_2S is undesirable in landfill gas, and because understanding the relationship allows landfill operators to better estimate the amount of H_2S produced. Examinations of the inputs of sulfate and outputs of H_2S from

other landfills also would give a better understanding of the relationship that exists between the two. Other factors such as climate and landfill operation can vary and will likely affect this relationship.

The third area of study of this paper involved the investigation of H_2S production from exhausted materials, or those materials that have already attenuated H_2S. These materials were placed in an environment similar to a landfill in that it is designed to be anaerobic with organic carbon is present. From this study, it was found that the material that is most inclined to regenerate H_2S was the sulfur cake. The column containing this material had sulfide concentrations of over 30 mg/L, which is more than twice the concentration of the column that had the next highest sulfide concentration. Likewise, the column that contained sulfur cake produced H_2S concentrations as high as 640 ppm. The highest concentration of H_2S in other columns was 6.2 ppm.

As mentioned, the purpose of this study was to investigate whether these materials would regenerate H_2S. Although it was found that the column containing the sulfur cake produced high concentrations of H_2S, further studies may be needed to affirm this result. The results of columns that did not produce high concentrations of H_2S do not necessarily indicate that these materials will not produce H_2S if placed in a landfill. The columns were maintained similar to a landfill, but conducted on a larger scale, may produce different results.

The final study examined different materials that could be used to prevent the production of H_2S. The columns contained C&D fines, which have been shown to produce H_2S when placed in a landfill environment, and mixed with other materials to see how/if they could inhibit H_2S production. The column containing only C&D fines

was intended to be the control column, producing uninhibited H_2S concentrations. In this experiment, this was not found as the control column failed to produce high concentrations of H_2S. In fact, several of the other columns produced H_2S concentrations higher than the control. However, none of these concentrations were higher than 5ppm, except one reading of 13 ppm.

Further study needs to be conducted on these materials to investigate if they can inhibit the production of H_2S. All materials have a potential ability for inhibition, yet the results of this experiment do not necessarily affirm this. If the columns were larger and therefore contained more C&D fines and organic carbon, then more H_2S may have been produced.

CHAPTER 6

RECOMMENDATIONS IF RESEARCH WERE REPEATED

- **Ex-situ Landfill Gas Experiment**
  - Ensured uniform particle size in experimental columns so as to improve landfill gas contact with the ash and improve kinetics
  - Investigated how much sulfur was present after experiment was conducted to see if H_2S attenuation was uniform throughout the experimental columns

- **C&D Waste Analysis**
  - Performed C&D study on different facilities outside of New England and the western United States to better assess sulfate content

- **Investigation of Hydrogen Sulfide Production from Exhausted Materials**
  - Added leachate from the landfill from the beginning of the experiment instead of RO water to be consistent
  - Used larger experimental columns so that sulfur production would be easier to notice as more may be produced in gas and leachate
  - Investigated the use of altering the temperature so as to simulate an environment more similar to that of a landfill
  - Normalized the amount of sulfur in each column to ensure that sulfides produced in the leachate and H_2S in the gas can also be normalized

- **Examination of Materials Used for Hydrogen Sulfide Inhibition**
  - Added leachate from the landfill from the beginning of the experiment instead of RO water to be consistent
  - Used larger experimental columns so that sulfur production would be easier to notice as more may be produced in gas and leachate
  - Examined the sulfate content of the leachate from the columns as much of the sulfur in the C&D fines is in sulfate form

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APPENDIX A

Experiment 1 Ex-situ Landfill Gas Experiment Results

Ash 1; Mass = 0.40kg; Volume = 1.11 Liters

Absolute Sample Time (min)	Well H_2S Concentration (ppm)	Flow rate (LPM)	Sample Concentration H_2S (ppm)	Concentration attenuated (ppm) H_2S	Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur Per Weight of Sample (mg/g)	Cumulative Attenuated Mass Sulfur Per Volume of Sample (mg/cm^3)
2	1800	21.24	0.16	1799.84	52.13	52.13	0.13	0.05
5	1800	21.24	0.16	1799.84	156.39	208.52	0.52	0.19
10	1800	21.24	0.16	1799.84	260.66	469.18	1.17	0.42
15	1800	21.24	0.15	1799.85	260.66	729.84	1.82	0.66
20	1800	21.24	0.17	1799.83	260.65	990.49	2.48	0.89
25	1800	21.24	0.17	1799.83	260.65	1251.14	3.13	1.13
30	1800	21.24	0.18	1799.82	260.65	1511.80	3.78	1.36
35	1800	21.24	0.16	1799.84	260.66	1772.45	4.43	1.60
40	1800	21.24	0.17	1799.83	260.65	2033.11	5.08	1.83
45	1800	21.24	0.16	1799.84	260.66	2293.76	5.73	2.06
50	1800	21.24	0.18	1799.82	260.65	2554.41	6.39	2.30
55	1800	21.24	0.19	1799.81	260.65	2815.06	7.04	2.53
60	1800	21.24	0.21	1799.79	260.65	3075.71	7.69	2.77
65	1800	21.24	0.20	1799.80	260.65	3336.36	8.34	3.00
70	1800	21.24	0.19	1799.81	260.65	3597.01	8.99	3.24
75	1800	21.24	0.17	1799.83	260.65	3857.67	9.64	3.47
80	1800	21.24	0.19	1799.81	260.65	4118.32	10.30	3.71
85	1800	21.24	0.18	1799.82	260.65	4378.97	10.95	3.94
90	1800	21.24	0.10	1799.90	260.66	4639.63	11.60	4.18
95	1800	21.24	0.20	1799.80	260.65	4900.28	12.25	4.41
100	1800	21.24	0.18	1799.82	260.65	5160.93	12.90	4.64
105	1800	21.24	0.20	1799.80	260.65	5421.58	13.55	4.88
110	1800	21.24	0.20	1799.80	260.65	5682.23	14.21	5.11
115	1800	21.24	0.21	1799.79	260.65	5942.88	14.86	5.35
120	1800	21.24	0.18	1799.82	260.65	6203.53	15.51	5.58
125	1800	21.24	0.19	1799.81	260.65	6464.18	16.16	5.82
130	1800	21.24	0.19	1799.81	260.65	6724.84	16.81	6.05
135	1800	21.24	0.18	1799.82	260.65	6985.49	17.46	6.29
140	1800	21.24	0.18	1799.82	260.65	7246.14	18.12	6.52
145	1800	21.24	0.18	1799.82	260.65	7506.79	18.77	6.76
150	1800	21.24	0.18	1799.82	260.65	7767.44	19.42	6.99
155	1800	21.24	0.20	1799.80	260.65	8028.09	20.07	7.23
160	1800	21.24	0.18	1799.82	260.65	8288.75	20.72	7.46
165	1800	21.24	0.19	1799.81	260.65	8549.40	21.37	7.69
170	1800	21.24	0.18	1799.82	260.65	8810.05	22.03	7.93
175	1800	21.24	0.18	1799.82	260.65	9070.70	22.68	8.16
180	1800	21.24	0.18	1799.82	260.65	9331.35	23.33	8.40
185	1800	21.24	0.19	1799.81	260.65	9592.01	23.98	8.63
190	1800	21.24	0.19	1799.81	260.65	9852.66	24.63	8.87
195	1800	21.24	0.19	1799.81	260.65	10113.31	25.28	9.10
200	1800	21.24	0.19	1799.81	260.65	10373.96	25.93	9.34
205	1800	21.24	0.17	1799.83	260.65	10634.61	26.59	9.57
210	1800	21.24	0.20	1799.80	260.65	10895.26	27.24	9.81
215	1800	21.24	0.20	1799.80	260.65	11155.91	27.89	10.04
220	1800	21.24	0.20	1799.80	260.65	11416.56	28.54	10.27
225	1800	21.24	0.20	1799.80	260.65	11677.21	29.19	10.51
230	1800	21.24	0.20	1799.80	260.65	11937.86	29.84	10.74
235	1800	21.24	0.20	1799.80	260.65	12198.51	30.50	10.98
240	1800	21.24	0.21	1799.79	260.65	12459.16	31.15	11.21
245	1800	21.24	0.21	1799.79	260.65	12719.80	31.80	11.45
250	1800	21.24	0.19	1799.81	260.65	12980.46	32.45	11.68
255	1800	21.24	0.20	1799.80	260.65	13241.10	33.10	11.92
260	1800	21.24	0.20	1799.80	260.65	13501.75	33.75	12.15
265	1800	21.24	0.20	1799.80	260.65	13762.40	34.41	12.39
270	1800	21.24	0.21	1799.79	260.65	14023.05	35.06	12.62
275	1800	21.24	0.20	1799.80	260.65	14283.70	35.71	12.86

Absolute Sample Time (min)	Well H_2S Concentration (ppm)	Flow rate (LPM)	Sample Concentration H_2S (ppm)	Concentration attenuated (ppm) H_2S	Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur Per Weight of Sample (mg/g)	Cumulative Attenuated Mass Sulfur Per Volume of Sample (mg/cm^3)
280	1800	21.24	0.20	1799.80	260.65	14544.35	36.36	13.09
285	1800	21.24	0.18	1799.82	260.65	14805.00	37.01	13.32
290	1800	21.24	0.21	1799.79	260.65	15065.65	37.66	13.56
295	1800	21.24	0.21	1799.79	260.65	15326.30	38.32	13.79
300	1800	21.24	0.21	1799.79	260.65	15586.95	38.97	14.03
305	1800	21.24	0.21	1799.79	260.65	15847.60	39.62	14.26
310	1800	21.24	0.21	1799.79	260.65	16108.24	40.27	14.50
315	1800	21.24	0.20	1799.80	260.65	16368.89	40.92	14.73
320	1600	21.24	0.19	1599.81	231.69	16600.58	41.50	14.94
322	1500	18.88	0.17	1499.83	77.23	16677.81	41.69	15.01
327	1500	18.88	0.15	1499.85	193.08	16870.88	42.18	15.18
332	1500	18.88	0.40	1499.60	193.04	17063.93	42.66	15.36
337	1500	18.88	50	1450.00	186.66	17250.59	43.13	15.53
340	1500	18.88	170	1330.00	102.73	17353.31	43.38	15.62
350	1500	18.88	150	1350.00	347.57	17700.88	44.25	15.93
360	1500	18.88	160	1340.00	345.00	18045.88	45.11	16.24
370	1500	18.88	160	1340.00	345.00	18390.88	45.98	16.55
380	1500	18.88	120	1380.00	355.30	18746.17	46.87	16.87
390	1400	18.88	200	1200.00	308.95	19055.12	47.64	17.15
400	1400	18.88	200	1200.00	308.95	19364.08	48.41	17.43
410	1400	18.88	190	1210.00	311.53	19675.60	49.19	17.71
420	1400	18.88	190	1210.00	311.53	19987.13	49.97	17.99
430	1400	18.88	200	1200.00	308.95	20296.08	50.74	18.27
440	1400	18.88	200	1200.00	308.95	20605.03	51.51	18.54
450	1800	18.88	180	1620.00	417.09	21022.12	52.56	18.92
452	1800	18.88	0.18	1799.82	92.68	21114.80	52.79	19.00
457	1800	18.88	0.19	1799.81	231.69	21346.49	53.37	19.21
462	1800	21.24	7.8	1792.20	259.55	21606.04	54.02	19.45
467	1800	21.24	50	1750.00	253.44	21859.47	54.65	19.67
470	1800	21.24	130	1670.00	145.11	22004.58	55.01	19.80
475	1800	21.24	350	1450.00	209.99	22214.57	55.54	19.99
480	1800	21.24	470	1330.00	192.61	22407.19	56.02	20.17
485	1800	21.24	570	1230.00	178.13	22585.32	56.46	20.33
490	1800	21.24	620	1180.00	170.89	22756.21	56.89	20.48
500	1800	21.24	650	1150.00	333.09	23089.30	57.72	20.78
510	1900	21.24	690	1210.00	350.47	23439.76	58.60	21.10
520	1900	21.24	700	1200.00	347.57	23787.33	59.47	21.41
530	1900	21.24	800	1100.00	318.61	24105.94	60.26	21.70
540	1900	21.24	760	1140.00	330.19	24436.13	61.09	21.99
550	1900	21.24	820	1080.00	312.81	24748.95	61.87	22.27
560	1900	21.24	820	1080.00	312.81	25061.76	62.65	22.56
570	1800	21.24	790	1010.00	292.54	25354.30	63.39	22.82
580	1800	21.24	790	1010.00	292.54	25646.84	64.12	23.08
590	1800	21.24	770	1030.00	298.33	25945.17	64.86	23.35
610	1800	25.96	100	1700.00	1203.63	27148.80	67.87	24.43
620	1800	23.60	760	1040.00	334.70	27483.50	68.71	24.74
630	1800	23.60	760	1040.00	334.70	27818.19	69.55	25.04
640	1900	23.60	780	1120.00	360.44	28178.64	70.45	25.36
650	1900	23.60	830	1070.00	344.35	28522.99	71.31	25.67
660	1900	23.60	800	1100.00	354.01	28877.00	72.19	25.99
670	1900	23.60	800	1100.00	354.01	29231.01	73.08	26.31
680	1800	23.60	1500	300.00	96.55	29327.55	73.32	26.39
690	1800	23.60	1600	200.00	64.37	29391.92	73.48	26.45
700	1800	23.60	1400	400.00	128.73	29520.65	73.80	26.57
710	1800	23.60	1800	0.00	0.00	29520.65	73.80	26.57

Ash 2; Mass = 0.60 kg; Volume = 0.515 Liters

Absolute Sample Time (min)	Well H_2S Concentration (ppm)	Flow rate (LPM)	Sample Concentration H_2S (ppm)	Concentration attenuated (ppm) H_2S	Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur Per Weight of Sample (mg/g)	Cumulative Attenuated Mass Sulfur Per Volume of Sample (mg/cm^3)
2	1300	14.16	0.11	1299.89	49.01	49.01	0.08	0.06
5	1700	14.16	0.008	1699.99	96.15	145.17	0.24	0.19
10	1700	14.16	0.016	1699.98	160.25	305.42	0.51	0.39
15	1700	16.52	7.8	1692.20	186.11	491.53	0.82	0.64
20	1700	16.52	50	1650.00	181.46	672.99	1.12	0.87
21	1700	16.52	55	1645.00	36.18	709.17	1.18	0.92
30	1700	16.52	130	1570.00	310.80	1019.97	1.70	1.32
40	1700	16.52	160	1540.00	338.73	1358.71	2.26	1.76
50	1700	16.52	180	1520.00	334.33	1693.04	2.82	2.19
60	1200	16.52	120	1080.00	237.55	1930.59	3.22	2.50
70	1200	16.52	110	1090.00	239.75	2170.35	3.62	2.81
80	1200	16.52	110	1090.00	239.75	2410.10	4.02	3.12
90	1200	16.52	110	1090.00	239.75	2649.85	4.42	3.43
100	1200	16.52	110	1090.00	239.75	2889.61	4.82	3.74
110	1200	16.52	230	970.00	213.36	3102.96	5.17	4.01
120	1200	16.52	200	1000.00	219.96	3322.92	5.54	4.30
130	1200	16.52	210	990.00	217.76	3540.68	5.90	4.58
140	1200	16.52	210	990.00	217.76	3758.44	6.26	4.86
150	1200	16.52	220	980.00	215.56	3973.99	6.62	5.14
160	1200	16.52	210	990.00	217.76	4191.75	6.99	5.42
170	1200	16.52	210	990.00	217.76	4409.51	7.35	5.70
180	1200	16.52	230	970.00	213.36	4622.87	7.70	5.98
190	1200	16.52	200	1000.00	219.96	4842.82	8.07	6.26
200	1200	16.52	240	960.00	211.16	5053.98	8.42	6.54
210	1200	16.52	250	950.00	208.96	5262.94	8.77	6.81
220	1200	16.52	260	940.00	206.76	5469.70	9.12	7.07
230	1200	16.52	210	990.00	217.76	5687.46	9.48	7.35
240	1100	16.52	380	720.00	158.37	5845.83	9.74	7.56
250	1100	16.52	400	700.00	153.97	5999.80	10.00	7.76
260	1100	16.52	460	640.00	140.77	6140.57	10.23	7.94
270	1100	16.52	550	550.00	120.98	6261.55	10.44	8.10
280	1100	16.52	590	510.00	112.18	6373.72	10.62	8.24
290	1100	16.52	670	430.00	94.58	6468.31	10.78	8.36
300	1100	16.52	570	530.00	116.58	6584.88	10.97	8.52
310	1100	16.52	710	390.00	85.78	6670.67	11.12	8.63
320	1100	16.52	1100	0.00	0.00	6670.67	11.12	8.63

Ash 3; Mass = 0.22kg; Volume = 1.02 Liters

Absolute Sample Time (min)	Well H_2S Concentration (ppm)	Flow rate (LPM)	Sample Concentration H_2S (ppm)	Concentration attenuated (ppm) H_2S	Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur Per Weight of Sample (mg/g)	Cumulative Attenuated Mass Sulfur Per Volume of Sample (mg/cm^3)
2	1500	9.44	0.00	1500.00	40.37	40.37	0.18	0.03
5	1500	9.44	0.00	1500.00	60.56	100.94	0.45	0.09
10	1500	9.44	0.00	1500.00	100.94	201.87	0.91	0.17
15	1500	9.44	0.01	1500.00	100.94	302.81	1.36	0.26
20	1500	9.44	0.01	1499.99	100.94	403.75	1.81	0.34
30	1500	9.44	0.02	1499.98	201.87	605.62	2.72	0.52
40	1500	11.80	0.02	1499.98	252.34	857.96	3.86	0.73
50	1500	11.80	0.01	1499.99	252.34	1110.30	4.99	0.95
60	1500	11.80	0.07	1499.93	252.33	1362.63	6.12	1.16
70	1500	11.80	1.50	1498.50	252.09	1614.72	7.26	1.38
80	1500	11.80	5.10	1494.90	251.48	1866.20	8.39	1.59
90	1500	11.80	13.00	1487.00	250.16	2116.36	9.51	1.81
100	1500	11.80	31.00	1469.00	247.13	2363.49	10.62	2.02
110	1500	11.80	50.00	1450.00	243.93	2607.42	11.72	2.23
113	1500	11.80	180.00	1320.00	66.62	2674.04	12.02	2.28
120	1400	11.80	260.00	1140.00	134.25	2808.28	12.62	2.40
130	1400	11.80	270.00	1130.00	190.10	2998.38	13.48	2.56
140	1400	11.80	310.00	1090.00	183.37	3181.75	14.30	2.72
150	1400	11.80	310.00	1090.00	183.37	3365.12	15.12	2.87
160	1400	11.80	420.00	980.00	164.86	3529.98	15.87	3.01
170	1400	11.80	420.00	980.00	164.86	3694.85	16.61	3.16
180	1400	11.80	420.00	980.00	164.86	3859.71	17.35	3.30
190	1400	11.80	430.00	970.00	163.18	4022.89	18.08	3.44
200	1400	11.80	430.00	970.00	163.18	4186.07	18.81	3.57
210	1400	11.80	460.00	940.00	158.13	4344.21	19.52	3.71
220	1400	11.80	480.00	920.00	154.77	4498.98	20.22	3.84
230	1400	11.80	560.00	840.00	141.31	4640.29	20.86	3.96
240	1200	11.80	640.00	560.00	94.21	4734.50	21.28	4.04
250	1200	11.80	790.00	410.00	68.97	4803.47	21.59	4.10
260	1200	11.80	900.00	300.00	50.47	4853.94	21.82	4.14
270	1200	11.80	1200.00	0.00	0.00	4853.94	21.82	4.14

Ash 4; Mass = 0.53 kg; Volume = 0.53 Liters

Absolute Sample Time (min)	Well H_2S Concentration (ppm)	Flow rate (LPM)	Sample Concentration H_2S (ppm)	Concentration attenuated (ppm) H_2S	Attenuated Mass H2S (mg)	Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur (mg)	Cumulative Attenuated Mass Sulfur Per Weight of Sample (mg/g)	Cumulative Attenuated Mass Sulfur Per Volume of Sample (mg/cm^3)
2	1400	9.44	0.00	1400.00	18.06	16.99	16.99	0.13	0.01
5	1400	11.80	0.00	1400.00	67.71	63.70	80.69	0.60	0.05
10	1400	16.52	0.00	1400.00	157.98	148.64	229.33	1.71	0.14
15	1400	18.88	0.00	1400.00	180.55	169.87	399.20	2.97	0.24
20	1400	18.88	0.00	1400.00	180.55	169.87	569.07	4.24	0.35
25	1400	18.88	0.01	1399.99	180.55	169.87	738.94	5.51	0.45
30	1400	18.88	0.01	1399.99	180.55	169.87	908.81	6.77	0.56
35	1400	18.88	0.02	1399.98	180.55	169.87	1078.68	8.04	0.66
40	1400	18.88	0.21	1399.79	180.52	169.85	1248.53	9.30	0.77
45	1400	18.88	0.80	1399.20	180.45	169.77	1418.30	10.57	0.87
50	1400	18.88	3.20	1396.80	180.14	169.48	1587.79	11.83	0.97
55	1400	18.88	5.90	1394.10	179.79	169.16	1756.94	13.09	1.08
60	1200	18.88	9.60	1190.40	153.52	144.44	1901.38	14.17	1.17
65	1200	18.88	21.00	1179.00	152.05	143.06	2044.44	15.23	1.25
70	1200	18.88	26.00	1174.00	151.40	142.45	2186.89	16.30	1.34
75	1200	18.88	29.00	1171.00	151.02	142.09	2328.98	17.35	1.43
80	1200	18.88	40.00	1160.00	149.60	140.75	2469.73	18.40	1.51
85	1200	18.88	44.00	1156.00	149.08	140.27	2609.99	19.45	1.60
90	1200	18.88	50.00	1150.00	148.31	139.54	2749.53	20.49	1.69
91	1200	18.88	60.00	1140.00	29.40	27.66	2777.19	20.69	1.70
100	1200	18.88	100.00	1100.00	255.35	240.25	3017.44	22.48	1.85
110	1200	18.88	160.00	1040.00	268.25	252.38	3269.82	24.37	2.00
120	1300	18.88	220.00	1080.00	278.56	262.09	3531.91	26.32	2.17
130	1300	18.88	380.00	920.00	237.30	223.26	3755.17	27.98	2.30
140	1300	18.88	380.00	920.00	237.30	223.26	3978.43	29.65	2.44
150	1300	18.88	410.00	890.00	229.56	215.98	4194.41	31.25	2.57
160	1300	18.88	490.00	810.00	208.92	196.57	4390.98	32.72	2.69
170	1300	18.88	590.00	710.00	183.13	172.30	4563.28	34.00	2.80
180	1300	18.88	200.00	1100.00	283.72	266.94	4830.22	35.99	2.96
190	1300	18.88	410.00	890.00	229.56	215.98	5046.20	37.60	3.09
200	1300	18.88	550.00	750.00	193.45	182.01	5228.20	38.96	3.21
210	1300	18.88	640.00	660.00	170.23	160.17	5388.37	40.15	3.30
220	1300	18.88	680.00	620.00	159.92	150.46	5538.83	41.27	3.40
230	1300	18.88	790.00	510.00	131.54	123.76	5662.59	42.20	3.47
240	1200	18.88	1100.00	100.00	25.79	24.27	5686.86	42.38	3.49
250	1200	18.88	1200.00	0.00	0.00	0.00	5686.86	42.38	3.49

APPENDIX B

Experiment 2 C&D Fines Analysis-Results

Sulfate Concentrations of C&D Fines from Eleven Analyzed Facilities

Facility	Sulfate Reading (%)	Average
MA_1	3.3	3.3
	3.3	
	3.2	
	3.1	
	3.6	
	3.2	
MA_2	0.31	1.6
	0.34	
	1.00	
	0.47	
	0.18	
	0.34	
	2.00	
	0.34	
	0.17	
	3.84	
	3.84	
	3.54	
	3.24	
	3.24	
MA_3	4.4	4.4
	5.9	
	1.2	
	4.6	
	9.3	
	4.7	
	4.8	
	5.5	
	3.4	
	2.8	
	3.7	
	2.8	
MA_4	3.6	3.7
	3.3	
	3.4	
	3.0	
	2.8	
	3.4	
	3.6	
	3.6	
	3.6	
	4.7	
	5.4	
	3.4	
MA_5	11.0	8.7
	9.8	
	9.6	
	8.9	
	5.0	
	9.5	
	12.0	
	5.0	
	12.0	
	6.2	
	11.0	
	4.7	

Facility	Sulfate Reading (%)	Average
MA_6	5.5	6.8
	12.0	
	8.4	
	6.9	
	4.4	
	8.9	
	4.9	
	6.1	
	6.0	
	5.2	
MA_7	7.0	3.2
	8.9	
	7.7	
	5.8	
	2.2	
	1.7	
	4.8	
	0.6	
	5.8	
	6.0	
	0.4	
	2.2	
	5.1	
	1.8	
	0.7	
	0.4	
	0.4	
	0.6	
	1.1	
	0.2	
MA_8	2.4	3.1
	3.6	
	3.42	
CA_1	7.37	7.4
	10.92	
	12.87	
CA_2	10.3	7.7
	9.8	
	9.5	
	5.2	
	6.4	
	5.0	
OR_1	16.3	15.2
	14.3	
	14.3	
	15.8	

Statistics	
Min	0.2
Max	16.3
Mean	5.1
Median	4.4
Std Dev	3.8
Number	102

APPENDIX C

Experiment 3: Investigation of Hydrogen Sulfide Production from Exhausted Materials

Contents of Each Column

Control

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	13.39	73%	22	0.609	98%
Dog Food	5.00	27%	513	0.010	2%
Total	18.39	100%	-	0.618	100%

Sulfur Cake

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	13.29	57%	22	0.604	98%
Dog Food	5.00	21%	513	0.010	2%
Sulfur Cake	5.00	21%	1300	0.004	1%
Total	23.29	100%	-	0.618	100%

Ash 1

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	12.77	46%	22	0.580	94%
Dog Food	5.00	18%	513	0.010	2%
Ash 1	10.00	36%	360	0.028	4%
Total	27.77	100%	-	0.618	100%

Ash 2

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	13.08	47%	22	0.594	96%
Dog Food	5.00	18%	513	0.010	2%
Ash 2	10.00	36%	730	0.014	2%
Total	28.08	100%	-	0.618	100%

Ash 3

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	12.22	45%	22	0.555	90%
Dog Food	5.00	18%	513	0.010	2%
Ash 3	10.00	37%	190	0.053	9%
Total	27.22	100%	-	0.618	100%

Ash 4

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	12.50	45%	22	0.568	92%
Dog Food	5.00	18%	513	0.010	2%
Ash 4	10.00	36%	251	0.040	6%
Total	27.50	100%	-	0.618	100%

ZeoBloc™ Paper

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
Paper	3.38	18%	22	0.153	25%
Dog Food	5.00	27%	513	0.010	2%
ZeoBloc™ Paper	10.00	54%	22	0.455	74%
Total	18.38	100%	-	0.618	100%

Experiment 3 Results

Column Data: Control

Day	mL removed	mL added	Total mL added	Total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	5.44	-	-	-	-	-	-
4	0	100	200	200	10.87	-	-	-	-	-	-
6	0	100	300	300	16.31	-	-	-	-	-	-
7	0	100	400	400	21.75	-	-	-	-	-	-
8	0	100	500	500	27.19	-	-	-	-	-	-
11	0	100	600	600	32.62	-	-	-	-	-	-
12	0	100	700	700	38.06	-	-	-	-	-	-
13	0	100	800	800	43.50	-	-	-	-	-	-
14	0	100	900	900	48.94	-	-	-	-	-	-
15	0	100	1000	1000	54.37	-	-	-	-	-	0.004
19	0	100	1100	1100	59.81	-	-	-	-	-	-
20	0	100	1200	1200	65.25	-	-	-	-	-	-
21	0	100	1300	1300	70.69	-	-	-	-	-	-
22	31	100	1400	1369	76.12	-	-	-	-	0.03	0
25	95	24	1424	1298	77.43	5.99	97	15.5	1.4	0.04	-
26	0	24	1448	1322	78.73	-	-	-	-	0.03	-
27	0	24	1472	1346	80.04	-	-	-	-	-	-
28	0	24	1496	1370	81.34	-	-	-	-	-	-
29	0	24	1520	1394	82.65	-	-	-	-	0.00	0.001
32	118	24	1544	1300	83.95	6.23	46.5	46	4.2	0.10	-
33	0	24	1568	1324	85.26	-	-	-	-	-	-
34	0	24	1592	1348	86.56	-	-	-	-	-	-
35	0	24	1616	1372	87.87	-	-	-	-	-	-
36	0	24	1640	1396	89.17	-	-	-	-	-	0.006
39	121	24	1664	1299	90.48	6.08	88.5	25.1	2.26	0.00	-
40	0	24	1688	1323	91.78	-	-	-	-	-	-
41	0	0	1688	1323	91.78	-	-	-	-	-	-
42	0	0	1688	1323	91.78	-	-	-	-	-	-
43	103	100	1788	1320	97.22	5.92	79.1	46	4.15	0.00	0
46	0	0	1788	1320	97.22	-	-	-	-	-	-
47	0	0	1788	1320	97.22	-	-	-	-	-	-
48	100	100	1888	1320	102.66	5.84	39.2	47.7	4.27	0.05	-
49	0	0	1888	1320	102.66	-	-	-	-	-	-
50	0	0	1888	1320	102.66	-	-	-	-	-	0.004
57	0	0	1888	1320	102.66	-	-	-	-	-	0
60	100	100	1988	1320	108.09	5.71	15.4	26	2.3	0.05	-
64	0	0	1988	1320	108.09	-	-	-	-	-	0.016
67	103	100	2088	1317	113.53	7.89	-283.2	7.5	0.64	3.25	-
71	0	0	2088	1317	113.53	-	-	-	-	-	0.003
74	107	100	2188	1310	118.97	7.51	-235	17.6	1.45	6.08	-
78	0	0	2188	1310	118.97	-	-	-	-	-	0.001
81	101	100	2288	1309	124.41	7.31	-211.5	18.8	1.59	3.28	-
85	-	0	2288	1309	124.41	-	-	-	-	-	0
89	110	100	2388	1299	129.84	7.35	-145.8	33	2.8	2.55	-
92	0	0	2388	1299	129.84	-	-	-	-	-	0
95	105	100	2488	1294	135.28	7.34	-184.8	28	2.31	2.73	-
99	0	0	2588	1294	135.28	-	-	-	-	-	0.56
102	110	100	2588	1284	140.72	7.4	-199	32.7	2.75	3.35	-
109	102	100	2688	1282	146.16	7.23	-191.6	39.3	3.35	4.78	-
113	0	0	2788	1282	151.59	-	-	-	-	-	0.88
117	103	100	2788	1279	151.59	7.24	-205.9	28.8	2.4	4.28	-
120	0	0	2888	1279	157.03	-	-	-		-	0.12
123	103	100	2888	1276	157.03	7.25	-188.9	33	2.77	3.43	-
127	0	0	2988	1276	162.47	-	-	-		-	0.75
130	105	100	2988	1271	162.47	7.39	-203	18	1.5	-	-
134	0	0	3088	1271	167.91	-	-	-		-	0.44
137	104	100	3088	1267	167.91	7.28	-312.6	43.6	3.6	0.70	-
141	0	0	3188	1267	173.34	-	-	-		-	0.009
144	105	100	3188	1262	173.34	7.37	-233	24.6	2.08	5.85	-
148	0	0	3288	1262	178.78	-	-	-		-	0.25
151	102	100	3288	1260	178.78	7.36	-210	19.8	1.69	3.90	-
155	0	0	3388	1260	184.22	-	-	-		-	0.21
158	103	100	3388	1257	184.22	7.73	-112	14.6	1.2	3.10	-
162	0	0	3388	1257	189.65	-	-	-		-	0.5

Column Data: Sulfur Cake

Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	4.29	-	-	-	-	-	-
4	68	100	200	132	8.59	8.06	113.7	60.6	5.82	4.63	-
6	91	100	300	141	12.88	6.38	-35.8	50	4.52	0.10	-
7	14	100	400	227	17.17	-	-	-	-	1.31	-
8	39	100	500	288	21.47	-	-	-	-	0.99	-
11	11	100	600	377	25.76	-	-	-	-	0.46	-
12	0	100	700	477	30.05	-	-	-	-	0.14	-
13	0	100	800	577	34.35	-	-	-	-	-	-
14	87	100	900	590	38.64	6	-95	34	3	0.76	-
15	100	24	924	514	39.67	6	18	39	4	-	0.035
19	0	24	948	538	40.70	-	-	-	-	-	-
20	0	24	972	562	41.73	-	-	-	-	-	-
21	0	24	996	586	42.76	-	-	-	-	-	-
22	0	24	1020	610	43.79	-	-	-	-	-	0.002
25	15	24	1044	619	44.82	-	-	-	-	0.69	-
26	0	24	1068	643	45.85	-	-	-	-	-	-
27	0	24	1092	667	46.88	-	-	-	-	-	-
28	0	24	1116	691	47.91	-	-	-	-	-	-
29	0	24	1140	715	48.94	-	-	-	-	0.00	0.002
32	24	24	1164	715	49.97	-	-	-	-	0.00	-
33	0	24	1188	739	51.00	-	-	-	-	0.00	-
34	0	24	1212	763	52.03	-	-	-	-	0.00	-
35	0	24	1236	787	53.07	-	-	-	-	-	-
36	0	24	1260	811	54.10	-	-	-	-	0.00	0.006
39	109	24	1284	726	55.13	-	-	-	-	0.00	-
40	0	24	1308	750	56.16	-	-	-	-	0.00	-
41	0	0	1308	750	56.16	-	-	-	-	0.00	-
42	0	0	1308	750	56.16	-	-	-	-	0.00	-
43	30	100	1408	820	60.45	-	-	-	-	1.70	0
46	0	0	1408	820	60.45	-	-	-	-	-	-
47	0	0	1408	820	60.45	-	-	-	-	-	-
48	65	100	1508	855	64.74	5.66	15.5	39.3	3.51	0.19	-
49	0	0	1508	855	64.74	-	-	-	-	-	-
50	0	0	1508	855	64.74	-	-	-	-	-	0
57	0	0	1508	855	64.74	0	0	0	0	0.00	0
60	60	100	1608	895	69.04	5.77	-0.5	29	2.5	0.03	-
64	0	0	1608	895	69.04	-	-	-	-	-	0.005
67	104	100	1708	891	73.33	7.9	-325.7	6.3	0.54	8.25	-
71	0	0	1708	891	73.33	-	-	-	-	-	0.004
74	20	100	1808	971	77.62	-	-	-	-	0.85	-
78	0	0	1808	971	77.62	-	-	-	-	-	0.003
81	67	100	1908	1004	81.92	7.1	-288.9	22	1.81	15.23	-
85	-	0	1908	1004	81.92	-	-	-	-	-	0
89	99	100	2008	1005	86.21	7.37	-199	29.5	2.48	2.93	-
92	-	0	2008	1005	86.21	-	-	-	-	-	0
95	101	100	2108	1004	90.50	7.17	-228.5	18.1	1.55	3.65	-
99	-	-	2108	1004	90.50	-	-	-	-	-	0.53
102	104	100	2208	1000	94.80	7.26	-254.5	29.5	2.45	11.08	
106	0	0	2208	1000	94.80	-	-	-	-	-	50
109	104	100	2308	996	99.09	7.19	-229.5	27.5	2.34	7.10	-
113	0	0	2308	996	99.09	-	-	-	-	-	0.024
117	100	100	2408	996	103.38	7.14	-237.9	20.3	1.71	5.45	-
120	0	0	2408	996	103.38	-	-	-	-	-	0.13
123	101	100	2508	995	107.68	7.18	-302.3	26.6	2.22	16.50	-
127	0	0	2508	995	107.68	-	-	-	-	-	0.74
130	65	100	2608	1030	111.97	7.35	-348	27.5	2.3	-	-
134	0	0	2608	1030	111.97	-	-	-	-	-	0.39
137	95	100	2708	1035	116.26	7.22	-355.5	38	3.1	33.00	-
141	0	0	2708	1035	116.26	-	-	-	-	-	1.6
144	102	100	2808	1033	120.56	7.34	-325	35.3	2.95	24.80	-
148	0	0	2808	1033	120.56	-	-	-	-	-	1.6
151	101	100	2908	1032	124.85	7.28	-309	30.8	2.6	31.60	-
155	0	0	2908	1032	124.85	-	-	-	-	-	190
158	98	100	3008	1034	129.14	7.89	-355	8.6	0.7	26.70	-
162	0	0	3008	1034	129.14	-	-	-	-	-	640

Column Data: Ash 1

Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100.00	100	3.60	-	-	-	-	-	-
4	34.5	100	200	165.5	7.20	-	-	-	-	0.66	-
6	51	100	300	214.5	10.80	5.28	-169	60.6	5.45	0.66	-
7	94	100	400	220.5	14.41	5.7	-257	17	1.55	0.875	-
8	98	100	500	222.5	18.01	5.71	-270.6	20.1	1.8	0.4375	-
11	100	100	600	222.5	21.61	5.88	-218.8	25.6	2.31	0.1875	-
12	98	100	700	224.5	25.21	6.33	-169	34.5	3.03	0.1125	-
13	99	100	800	225.5	28.81	6.2	55	29.5	2.7	0.1875	-
14	94	24	824	156	29.68	6	-77	24	2	0	-
15	0	24	848	180	30.54	-	-	-	-	-	0.004
19	0	24	872	203.5	31.41	-	-	-	-	-	-
20	0	24	896	227.5	32.27	-	-	-	-	-	-
21	0	24	920	251.5	33.13	-	-	-	-	-	-
22	110	24	944	165.5	34.00	6.48	-103.1	18.9	1.7	1.2125	0.005
25	0	24	968	189.5	34.86	-	-	-	-	1.2125	-
26	0	24	992	213.5	35.73	-	-	-	-	-	-
27	0	24	1016	237.5	36.59	-	-	-	-	-	-
28	0	24	1040	261.5	37.46	-	-	-	-	-	-
29	122	24	1064	163.5	38.32	6.65	-63.9	32.5	2.85	0.55	0
32	0	24	1088	187.5	39.19	-	-	-	-	-	-
33	0	24	1112	211.5	40.05	-	-	-	-	-	-
34	122	24	1136	113.5	40.91	-	-	-	-	0	-
35	0	24	1160	137.5	41.78	-	-	-	-	-	-
36	105	24	1184	56.5	42.64	6.51	-39.3	34.4	3.04	-	0.006
39	0	24	1208	80.5	43.51	-	-	-	-	-	-
40	0	24	1232	104.5	44.37	-	-	-	-	-	-
41	0	24	1256	128.5	45.24	-	-	-	-	-	-
42	0	24	1280	152.5	46.10	-	-	-	-	-	-
43	123	100	1380	129.5	49.70	6.37	71.5	33.5	2.98	0.2625	0
46	0	0	1380	129.5	49.70	-	-	-	-	-	-
47	0	0	1380	129.5	49.70	-	-	-	-	-	-
48	100	100	1480	129.5	53.30	6.3	-23.5	25	2.27	0.0625	-
49	0	0	1480	129.5	53.30	-	-	-	-	-	-
50	0	0	1480	129.5	53.30	-	-	-	-	-	0
57	0	0	1480	129.5	53.30	-	-	-	-	-	0
60	100	100	1580	129.5	56.91	6.09	-17.8	30.2	2.73	0.075	-
64	0	0	1580	129.5	56.91	-	-	-	-	-	0.002
67	101	100	1680	128.5	60.51	8.01	-197.9	21	1.08	2.125	-
71	0	0	1680	128.5	60.51	-	-	-	-	-	0.003
74	103	100	1780	125.5	64.11	7.61	-235	41.6	3.5	7.7	-
78	0	0	1780	125.5	64.11	-	-	-	-	-	0.14
81	100	100	1880	125.5	67.71	7.09	-231.9	25.5	2.19	2.725	-
85	0	0	1880	125.5	67.71	-	-	-	-	-	0
89	105	100	1980	120.5	71.31	7.16	-203.1	27.7	2.34	0.925	-
92	0	0	1980	120.5	71.31	-	-	-	-	-	0
95	100	100	2080	120.5	74.91	7.11	-272.5	15.3	1.31	15.7	-
99	0	0	2080	120.5	74.91	-	-	-	-	-	0.49
102	101	100	2180	120	78.51	7.06	-235	30.1	2.55	6.425	-
109	110	100	2280	110	82.12	7.2	-236.8	23.6	2.01	3.875	-
113	0	0	2280	110	82.12	-	-	-	-	-	0.004
117	105	100	2380	104.5	85.72	7.14	-248.9	18.1	1.52	7.9	-
120	0	0	2380	104.5	85.72	-	-	-	-	-	0.2
123	105	100	2480	99.5	89.32	7.19	-186.5	23.6	1.98	0.975	-
127	0	0	2480	99.5	89.32	-	-	-	-	-	0.69
130	105	100	2580	94.5	92.92	7.32	-255	30.5	2.54	-	-
134	0	0	2580	94.5	92.92	-	-	-	-	-	0.36
137	105	100	2680	89.5	96.52	7.37	-273	29.9	2.46	1.9	-
141	0	0	2680	89.5	96.52	-	-	-	-	-	0.4
144	103	100	2780	86.5	100.12	7.35	-285.8	33.7	2.75	7.025	-
148	0	0	2780	86.5	100.12	-	-	-	-	-	0.28
151	93	100	2880	93.5	103.73	7.35	-279	28.3	2.33	8.75	-
155	0	0	2880	93.5	103.73	-	-	-	-	-	0.29
158	103	100	2980	90.5	107.33	7.32	-336	13.5	1.09	6.4	-
162	0	0	2980	90.5	107.33	-	-	-	-	-	0.38

Column Data: Ash 2

Day	mL removed	mL added	Total added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	3.56	-	-	-	-	-	-
4	10	100	200	190	7.12	-	-	-	-	0.07	-
6	78	100	300	212	10.69	5.89	-205	58.5	5.24	0.18	-
7	94	100	400	218	14.25	5.99	-225	50.7	4.15	2.50	-
8	99	100	500	219	17.81	5.87	-220.6	35	3.1	0.24	-
11	99	100	600	220	21.37	6.2	-123	25.5	2.3	0.09	-
12	99	100	700	221	24.93	6.69	-112	34	3.02	0.04	-
13	97	100	800	224	28.49	6.32	198.1	34.6	3.12	0.09	-
14	100	24	824	148	29.35	7	-34	23	2	-	-
15	0	24	848	172	30.20	-	-	-	-	-	0.001
19	0	24	872	196	31.06	-	-	-	-	-	-
20	0	24	896	220	31.91	-	-	-	-	-	-
21	0	24	920	244	32.77	-	-	-	-	-	-
22	105	24	944	163	33.62	6.91	-4.3	20.1	1.76	0.16	0.002
25	0	24	968	187	34.48	-	-	-	-	0.16	-
26	0	24	992	211	35.33	-	-	-	-	-	-
27	0	24	1016	235	36.19	-	-	-	-	-	-
28	0	24	1040	259	37.04	-	-	-	-	-	-
29	115	24	1064	168	37.90	6.92	32	36	3.25	0.01	0.001
32	0	24	1088	192	38.75	-	-	-	-	-	-
33	0	24	1112	216	39.61	-	-	-	-	-	-
34	115	24	1136	125	40.46	-	-	-	-	0.00	-
35	0	24	1160	149	41.32	-	-	-	-	-	-
36	118	24	1184	55	42.17	6.8	42.4	30.3	2.74	-	0.003
39	0	24	1208	79	43.03	-	-	-	-	-	-
40	0	24	1232	103	43.88	-	-	-	-	-	-
41	0	24	1256	127	44.74	-	-	-	-	-	-
42	0	24	1280	151	45.59	-	-	-	-	-	-
43	97	100	1380	154	49.15	6.49	176	23	2.1	0.10	0
46	0	0	1380	154	49.15	-	-	-	-	-	-
47	0	0	1380	154	49.15	-	-	-	-	-	-
48	95	100	1480	159	52.72	6.56	-25.7	13.2	1.19	0.10	-
49	0	0	1480	159	52.72	-	-	-	-	-	-
50	0	0	1480	159	52.72	-	-	-	-	-	-
57	0	0	1480	159	52.72	0	0	0	0	0.00	0.001
60	95	100	1580	164	56.28	6.78	-55	24.9	2.23	0.03	-
64	0	0	1580	164	56.28	-	-	-	-	-	0.07
67	100	100	1680	164	59.84	8.1	-215.9	19.2	1.64	4.93	-
71	0	0	1680	164	59.84	-	-	-	-	-	0.14
74	102	100	1780	162	63.40	7.62	-269.1	12.6	1.07	12.23	-
78	0	0	1780	162	63.40	-	-	-	-	-	0.032
81	110	100	1880	152	66.96	7.31	-283.5	22.2	1.85	13.60	-
85	-	0	1880	152	66.96	-	-	-	-	-	0
89	101	100	1980	151	70.52	7.53	-255	20	1.73	9.58	-
92	-	0	1980	151	70.52	-	-	-	-	-	0
95	110	100	2080	141	74.09	7.48	-242.6	10.2	0.87	4.08	-
99	-	-	2080	141	74.09	-	-	-	-	-	0.45
102	110	100	2180	131	77.65	7.58	-198	20.7	1.75	1.80	-
109	110	100	2280	121	81.21	7.47	-155.9	25.6	2.1	0.70	-
113	0	0	2280	121	81.21	-	-	-	-	-	0
117	105	100	2380	116	84.77	7.48	-206.5	16.8	1.4	0.98	-
120	0	0	2380	116	84.77	-	-	-	-	-	0.25
123	103	100	2480	113	88.33	7.54	-88	30.3	2.53	0.08	-
127	0	0	2480	113	88.33	-	-	-	-	-	0.46
130	105	100	2580	108	91.90	7.67	-142.8	28.1	2.35	0.00	-
134	0	0	2580	108	91.90	-	-	-	-	-	0.27
137	93	100	2680	115	95.46	7.24	-303	33	2.75	0.30	-
141	0	0	2680	115	95.46	-	-	-	-	-	0.29
144	107	100	2780	108	99.02	7.69	-251.2	21.5	1.78	0.25	-
148	0	0	2780	108	99.02	-	-	-	-	-	0.17
151	98	100	2880	110	102.58	7.7	-179	25.6	2.12	0.25	-
155	0	0	2880	110	102.58	-	-	-	-	-	1.4
158	100	100	2980	110	106.14	7.68	-301	12.5	1.03	0.65	-
162	0	0	2980	110	106.14	-	-	-	-	-	1.5

Column Data: Ash 3

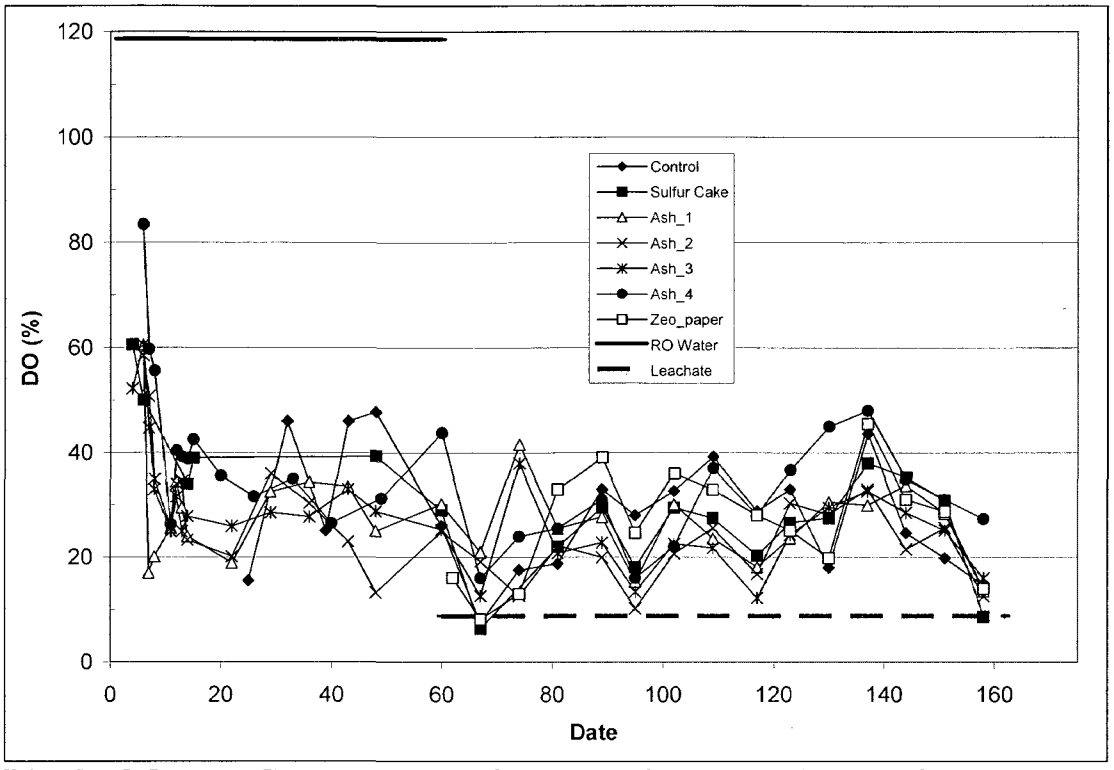
Day	mL removed	mL added	tal mL adde	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	3.67	-	-	-	-	-	-
4	53	100	200	148	7.35	6.48	42	52.2	4.81	0.16	-
6	74	100	300	174	11.02	6.32	4	60.5	5.3	0.00	-
7	80	100	400	194	14.70	6.34	-32	44.7	4.36	0.33	-
8	93	100	500	201	18.37	6.48	-60.8	33	2.98	0.35	-
11	98	100	600	203	22.04	6.38	-72.1	24.9	2.16	0.05	-
12	98	100	700	205	25.72	6.44	-56.6	31.5	2.8	0.39	-
13	97	100	800	208	29.39	6.18	98.8	24.9	2.13	0.05	-
14	100	24	824	132	30.27	6	-33	28	2	-	-
15	0	24	848	156	31.16	-	-	-	-	-	0.008
19	0	24	872	180	32.04	-	-	-	-	-	-
20	0	24	896	204	32.92	-	-	-	-	-	-
21	0	24	920	228	33.80	-	-	-	-	-	-
22	105	24	944	147	34.68	6.25	-180	25.9	2.25	0.18	0.009
25	0	24	968	171	35.56	-	-	-	-	0.18	-
26	0	24	992	195	36.45	-	-	-	-	-	-
27	0	24	1016	219	37.33	-	-	-	-	-	-
28	0	24	1040	243	38.21	-	-	-	-	-	-
29	112	24	1064	155	39.09	6.57	-61.5	28.5	2.55	0.04	0.004
32	0	24	1088	179	39.97	-	-	-	-	-	-
33	0	24	1112	203	40.85	-	-	-	-	-	-
34	112	24	1136	115	41.74	-	-	-	-	0.00	-
35	0	24	1160	139	42.62	-	-	-	-	-	-
36	105	24	1184	58	43.50	6.57	-66.5	27.7	2.21	-	0.006
39	0	24	1208	82	44.38	-	-	-	-	-	-
40	0	24	1232	106	45.26	-	-	-	-	-	-
41	0	24	1256	130	46.14	-	-	-	-	-	-
42	0	24	1280	154	47.03	-	-	-	-	-	-
43	103	100	1380	151	50.70	6.59	43.4	33	2.9	0.26	0
46	0	0	1380	151	50.70	-	-	-	-	-	-
47	0	0	1380	151	50.70	-	-	-	-	-	-
48	99	100	1480	152	54.37	6.53	-21.5	28.8	2.55	0.04	-
49	0	0	1480	152	54.37	-	-	-	-	-	-
50	0	0	1480	152	54.37	-	-	-	-	-	0
57	0	0	1480	152	54.37	-	-	-	-	-	-
60	97	100	1580	155	58.05	6.41	-25.7	25.3	2.26	0.05	-
64	0	0	1580	155	58.05	-	-	-	-	-	0.017
67	105	100	1680	150	61.72	8.05	-197.9	12.6	1.8	2.00	-
71	0	0	1680	150	61.72	-	-	-	-	-	0.005
74	100	100	1780	150	65.40	7.75	-214.8	38	3.1	4.75	-
78	0	0	1780	150	65.40	-	-	-	-	-	0
81	99	100	1880	151	69.07	7.37	-280.9	20.8	1.75	9.90	-
85	0	0	1880	151	69.07	-	-	-	-	-	0
89	101	100	1980	150	72.74	7.37	-249	22.8	1.91	9.93	-
92	0	0	1980	150	72.74	-	-	-	-	-	0
95	100	100	2080	150	76.42	7.27	-249.1	13.4	1.13	9.28	-
99	0	0	2080	150	76.42	-	-	-	-	-	0.51
102	97	100	2180	153	80.09	7.53	-251.3	22.6	1.9	8.68	
109	100	100	2280	153	83.77	7.32	-229.8	21.8	1.86	6.43	
113	0	0	2280	153	83.77	-	-	-	-	-	0.002
117	103	100	2380	150	87.44	7.37	-247.1	12.2	1.03	7.83	-
120	0	0	2380	150	87.44	-	-	-	-	-	0.18
123	102	100	2480	148	91.11	7.35	-197.7	24.3	2.02	1.25	-
127	0	0	2480	148	91.11	-	-	-	-	-	0.57
130	105	100	2580	143	94.79	7.49	-215.2	29.5	2.46	-	-
134	0	0	2580	143	94.79	-	-	-	-	-	0.33
137	93	100	2680	150	98.46	7.37	-273	32.6	2.71	0.23	-
141	0	0	2680	150	98.46	-	-	-	-	-	0.55
144	100	100	2780	150	102.14	7.49	-267.1	28.5	2.39	0.98	-
148	0	0	2780	150	102.14	-	-	-	-	-	0.18
151	102	100	2880	148	105.81	7.53	-239	25.1	2.08	1.38	-
155	0	0	2880	148	105.81	-	-	-	-	-	0.24
158	102	100	2980	146	109.48	7.5	-266	16	1.32	0.25	-
162	0	0	2980	146	109.48	-	-	-	-	-	0.35

Column Data: Ash 4

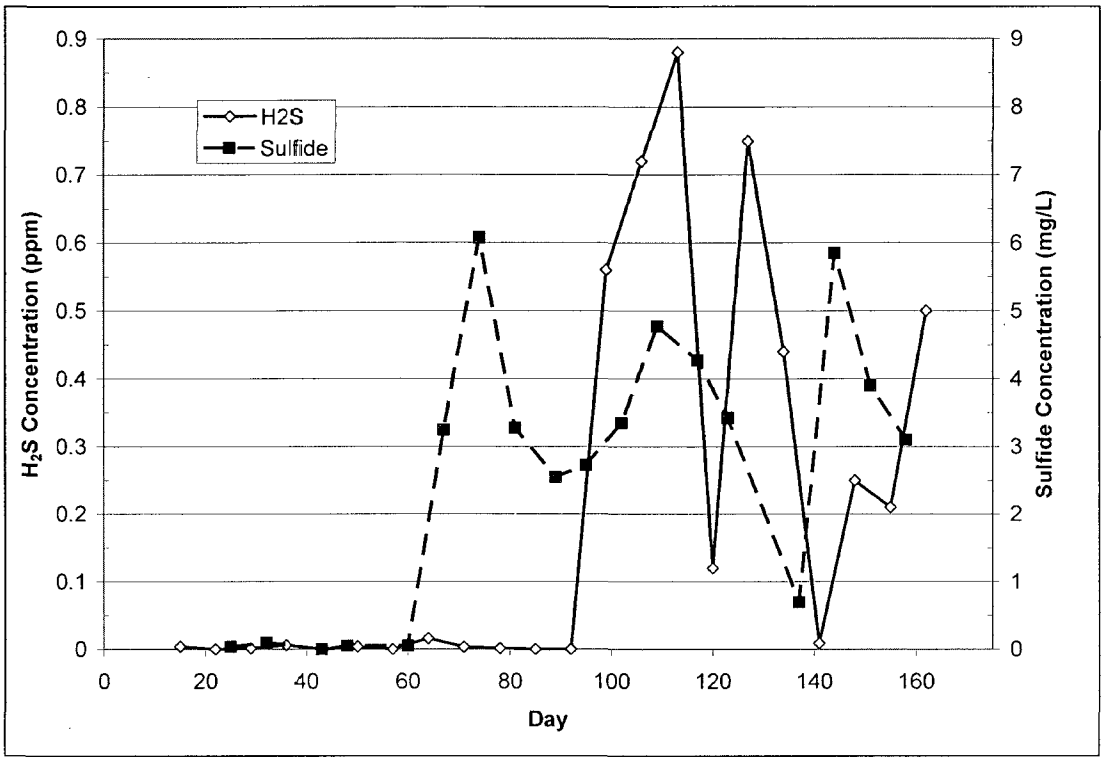
Day	mL removed	mL added	total added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	3.64	-	-	-	-	-	-
4	13	100	200	187	7.27	-	-	-	-	0.10	-
6	51	100	300	236	10.91	6.05	-228.5	83.4	7.65	0.42	-
7	91	100	400	245	14.55	6.19	50.5	59.7	7.65	0.56	-
8	76	100	500	269	18.18	6.33	-264.5	55.6	4.9	0.39	-
11	75	100	600	294	21.82	6.45	-86	26.3	2.36	0.34	-
12	80	100	700	314	25.45	6.57	7.1	40.4	3.67	0.11	-
13	66	100	800	348	29.09	6.53	-54.1	39.2	3.45	0.34	-
14	75	100	900	373	32.73	7	49	39	4	0.25	-
15	46	100	1000	427	36.36	6	1	43	4	-	0.008
19	7	100	1100	520	40.00	-	-	-	-	-	-
20	50	100	1200	570	43.64	6.64	210.6	35.6	3.24	0.10	-
21	1	100	1300	669	47.27	-	-	-	-	-	-
22	3	100	1400	766	50.91	-	-	-	-	0.00	0.009
25	60	100	1500	806	54.55	-	-	-	-	0.00	-
26	99	24	1524	731	55.42	6.13	199.2	31.6	2.82	0.01	-
27	0	24	1548	755	56.29	-	-	-	-	-	-
28	0	24	1572	779	57.16	-	-	-	-	-	-
29	0	24	1596	803	58.04	-	-	-	-	-	0.003
32	0	24	1620	827	58.91	-	-	-	-	-	-
33	121	24	1644	730	59.78	6.31	195	35	3.16	0.11	-
34	0	24	1668	754	60.65	-	-	-	-	-	-
35	0	24	1692	778	61.53	-	-	-	-	-	-
36	0	24	1716	802	62.40	-	-	-	-	-	0
39	0	24	1740	826	63.27	-	-	-	-	-	-
40	120	24	1764	730	64.15	6.36	130	26.5	2.4	-	-
41	0	0	1764	730	64.15	-	-	-	-	-	-
42	0	0	1764	730	64.15	-	-	-	-	-	-
43	0	0	1764	730	64.15	-	-	-	-	-	0
46	125	100	1864	705	67.78	-	-	-	-	-	-
47	0	0	1864	705	67.78	-	-	-	-	-	-
48	0	0	1864	705	67.78	-	-	-	-	-	-
49	97	100	1964	708	71.42	6.3	27	31.2	2.77	0.38	-
50	0	0	1964	708	71.42	-	-	-	-	-	0.001
57	0	0	1964	708	71.42	0	0	0	0	0.00	0
60	105	100	2064	703	75.05	6.35	12.5	43.8	3.98	0.01	
64	0	0	2064	703	75.05	-	-	-	-	-	0.057
67	99	100	2164	704	78.69	7.97	-240.7	16	1.32	1.50	
71	0	0	2164	704	78.69	-	-	-	-	-	0.011
74	103	100	2264	701	82.33	7.57	-200	24	2	1.40	-
78	0	0	2264	701	82.33	-	-	-	-	-	0.002
81	105	100	2364	696	85.96	7.36	-117.4	25.5	2	0.20	-
85	0	0	2364	696	85.96	-	-	-	-	-	0.14
89	102	100	2464	694	89.60	7.33	-94	31	2.6	0.03	-
92	0	0	2464	694	89.60	-	-	-	-	-	0
95	102	100	2564	692	93.24	7.3	-147.8	16	1.39	0.33	-
99	0	0	2564	692	93.24	-	-	-	-	-	0.001
102	110	100	2664	682	96.87	7.3	-154.9	22.1	1.88	0.78	-
109	100	100	2764	682	100.51	8.57	-143	37.1	3.13	1.00	-
113	0	0	2764	682	100.51	-	-	-	-	-	0.001
117	100	100	2864	682	104.14	7.26	-90.9	28	2.3	0.03	-
120	0	0	2864	682	104.14	-	-	-	-	-	0.35
123	105	100	2964	677	107.78	7.27	-2.9	36.7	3.1	0.00	-
127	0	0	2964	677	107.78	-	-	-	-	-	0.48
130	105	100	3064	672	111.42	7.54	-113	45	3.85	0.18	-
134	0	0	3064	672	111.42	-	-	-	-	-	0.27
137	102	100	3164	670	115.05	7.39	92	48	3.98	0.35	-
141	0	0	3164	670	115.05	-	-	-	-	-	0.28
144	105	100	3264	665	118.69	7.41	-142	34.9	2.88	0.58	-
148	0	0	3264	665	118.69	-	-	-	-	-	0.11
151	99	100	3364	666	122.33	7.42	-159	31	2.6	0.30	-
155	0	0	3364	666	122.33	-	-	-	-	-	0.13
158	105	100	3464	661	125.96	7.69	-240	27.3	2.28	0.20	-
162	0	0	3464	661	125.96	-	-	-	-	-	0.17

Column Data: Zeobloc ™ Paper

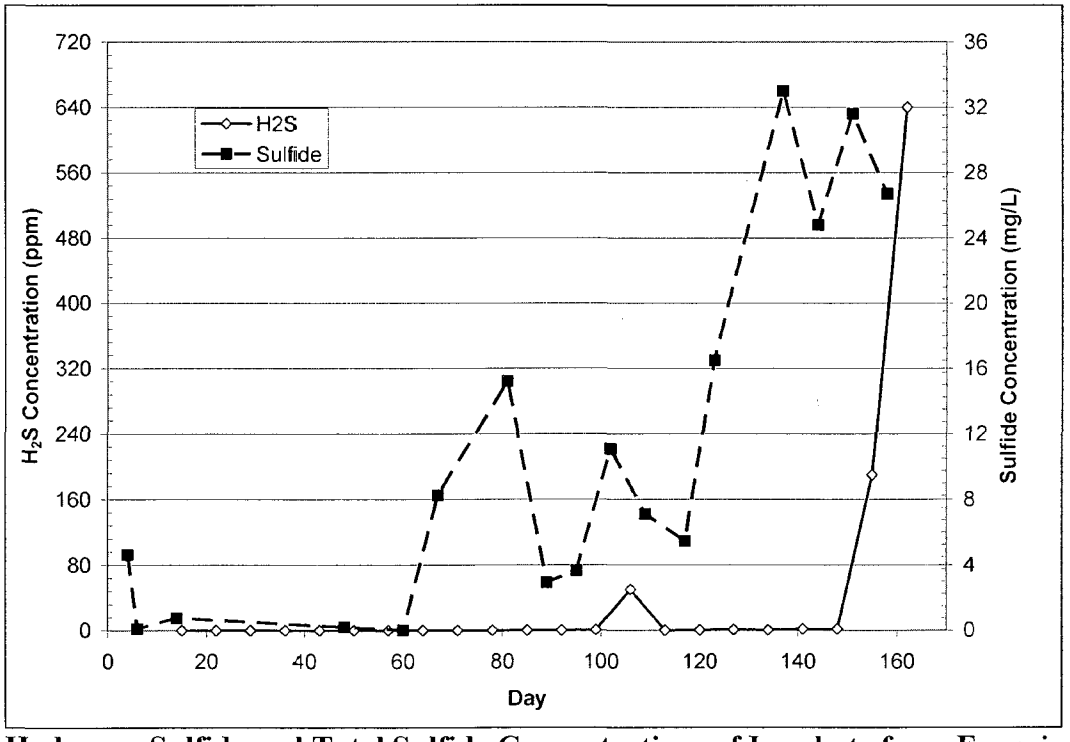
Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
60	0	100	100	100	5.44	-	-	-	-	-	-
61	0	100	200	200	10.88	-	-	-	-	-	-
62	136	100	300	164	16.33	7.65	-231.5	16.1	1.31	5	-
64	0	0	300	164	16.33	-	-	-	-	-	0.007
67	105	100	400	159	21.77	7.73	-319.4	8.1	0.68	8.25	-
71	0	0	400	159	21.77	-	-	-	-	-	0.007
74	102	100	500	157	27.21	7.09	-307.6	13	1.09	14.375	-
78	0	0	500	157	27.21	-	-	-	-	-	0.093
81	106	100	600	151	32.65	6.87	-218	33	2.8	10.625	-
85	0.00	0.00	600	151	32.65	-	-	-	-	-	0.26
89	102	100	700	149	38.09	7.01	-295	39.1	3.27	12.725	-
92	0	0	700	149	38.09	-	-	-	-	-	0
95	99	100	800	150	43.53	7.01	-281.9	24.7	2.08	11.725	-
99	0	0	900	150	48.98	-	-	-	-	-	0.008
102	100	100	900	150	48.98	7.03	-110.1	36.1	2.69	12.75	-
109	105	100	1000	145	54.42	7.06	-255.9	32.9	2.81	11.275	-
113	0	0	1100	145	59.86	-	-	-	-	-	0.017
117	105	100	1100	140	59.86	7.26	-90.9	28	2.3	0.025	-
120	0	0	1200	140	65.30	-	-	-	-	-	0.002
123	105	100	1200	135	65.30	7.13	-274.5	25.1	2.09	16.5	-
127	0	0	1300	135	70.74	-	-	-	-	-	0.87
130	98	100	1300	137	70.74	7.31	-295	19.8	1.68	-	-
134	0	0	1400	137	76.18	-	-	-	-	-	0.4
137	105	100	1400	132	76.18	7.1	-315	45.5	3.82	5.425	-
141	0	0	1500	132	81.63	-	-	-	-	-	2.3
144	105	100	1500	127	81.63	7.17	-281	31	2.53	10.125	-
148	0	0	1600	127	87.07	-	-	-	-	-	0.71
151	105	100	1600	122	87.07	7.18	-273	28.7	2.82	15.7	-
155	0	0	1700	122	92.51	-	-	-	-	-	6.2
158	110	100	1700	112	92.51	7.64	-340.5	14	1.16	9.4	-
162	0	0	1800	112	97.95	-	-	-	-	-	1.8



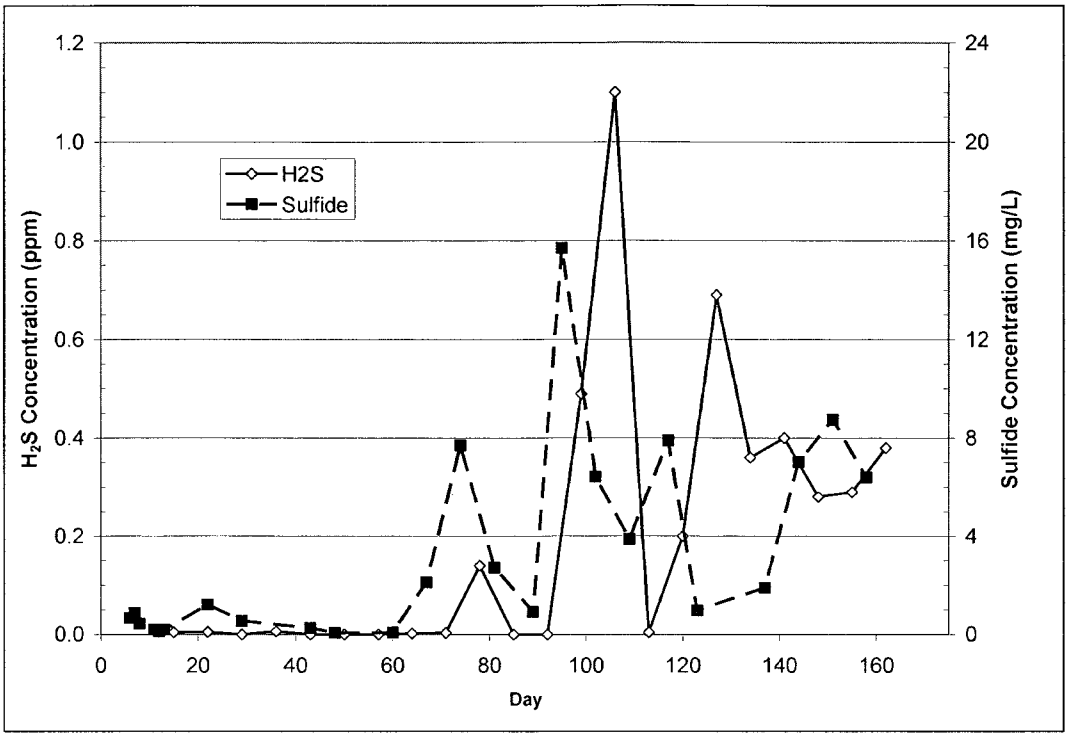
Dissolved Oxygen Concentrations of Leachate from Experimental Columns



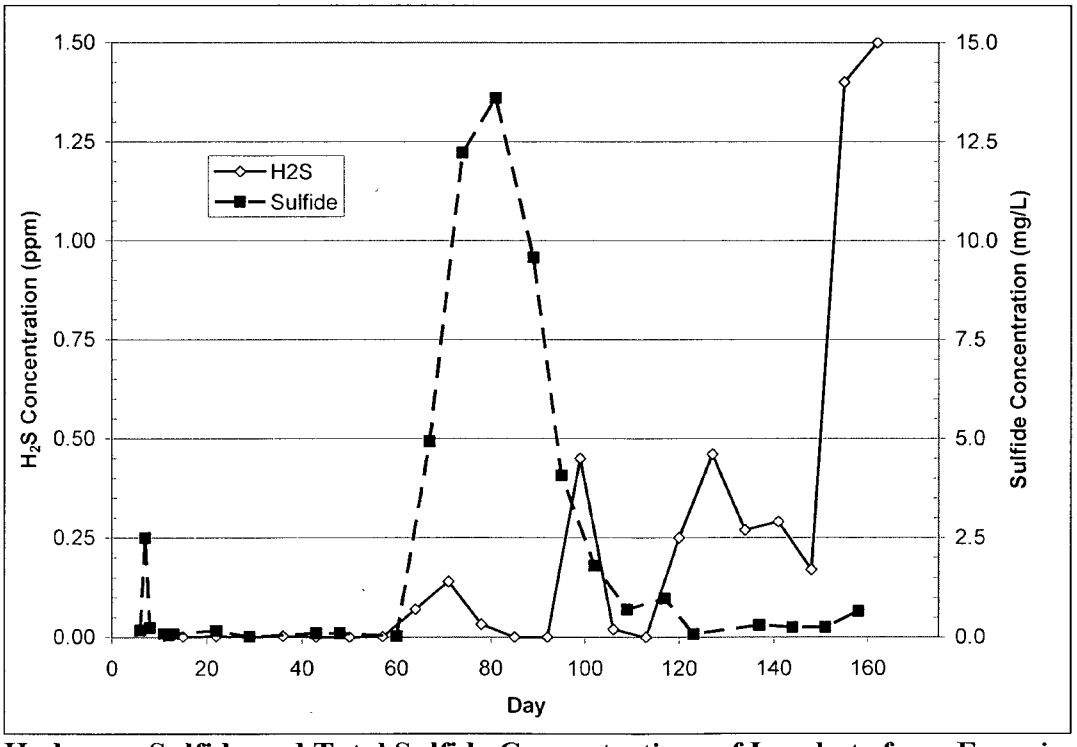
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Control



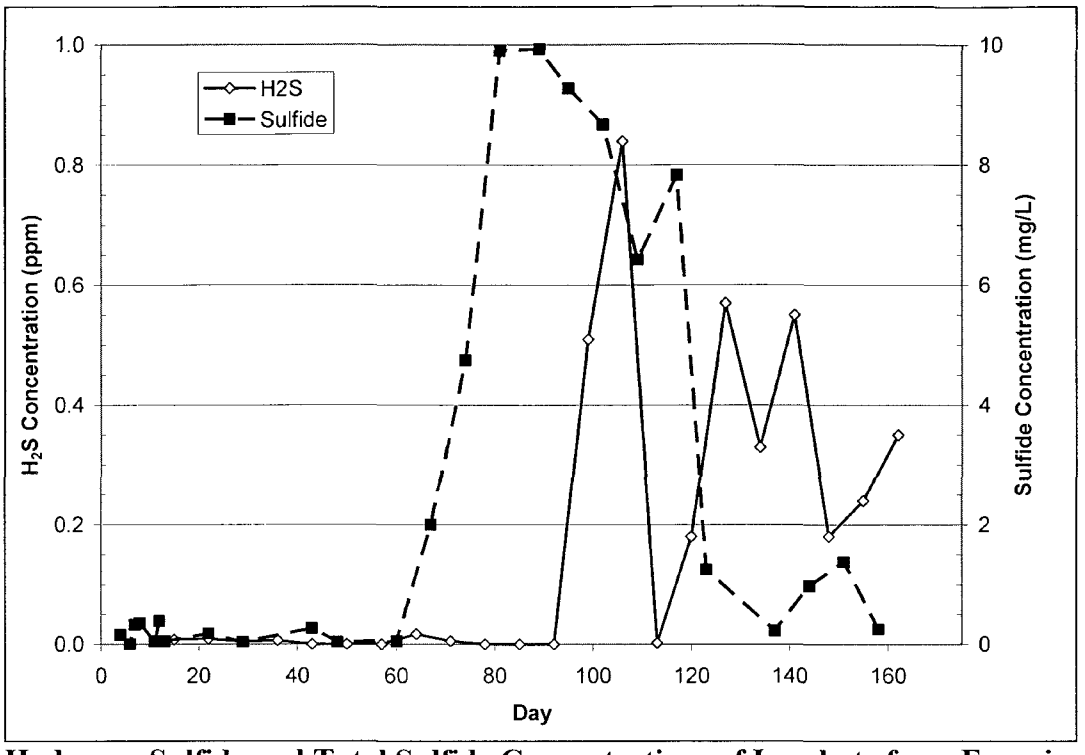
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Sulfur Cake



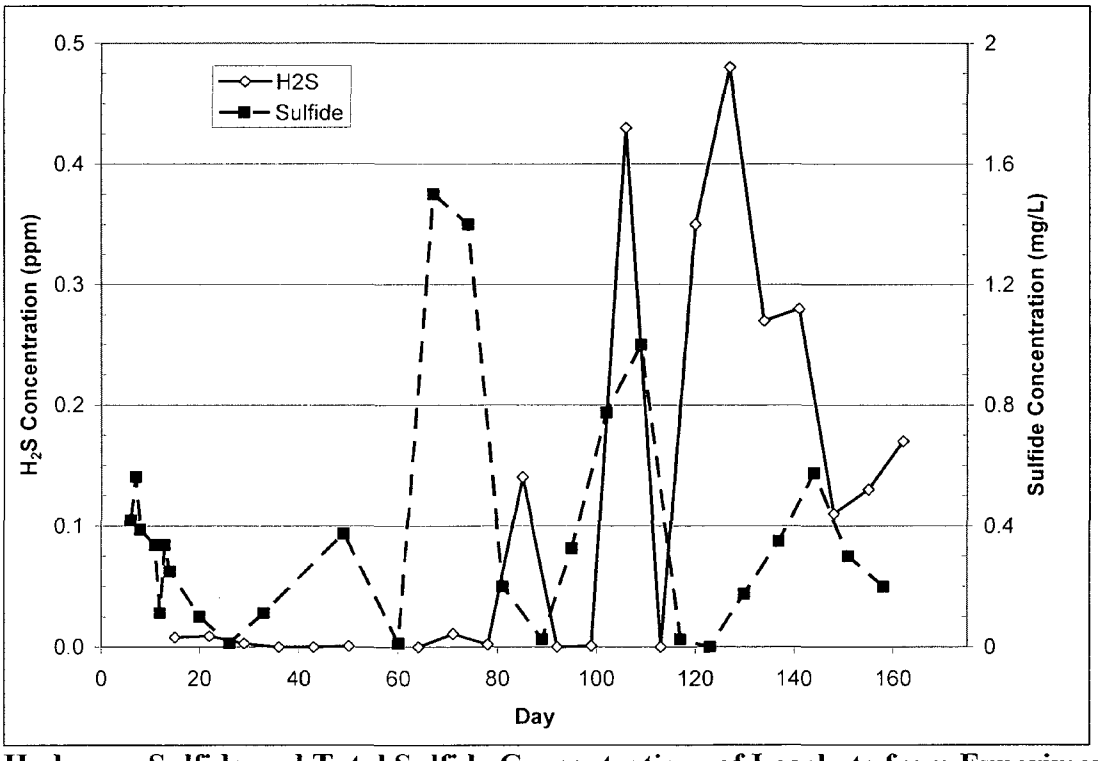
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Ash 1



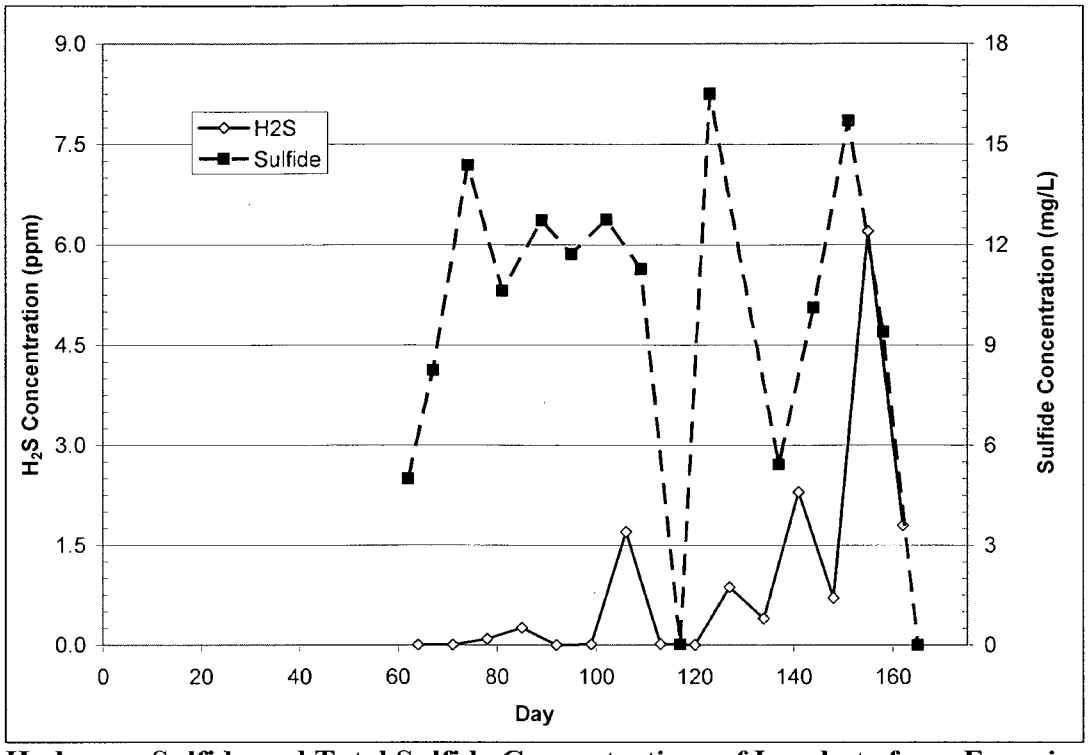
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Ash 2



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Ash 3



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Ash 4



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Zeobloc

APPENDIX D

Experiment 4: Examination of Materials Used for Hydrogen Sulfide Inhibition

Contents of Each Column

C&D Fines

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	423.42	100%	685.4	0.618	100%
Total	423.42	100%	-	0.618	100%

C&D Fines + $Ca(OH)_2$_1

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	392.97	80%	685	0.573	93%
$Ca(OH)_2$	98.24	20%	2211	0.044	7%
Total	491.21	100%	-	0.618	100%

C&D Fines + $Ca(OH)_2$_2

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	392.97	80%	685	0.573	93%
$Ca(OH)_2$	98.24	20%	2211	0.044	7%
Total	491.21	100%	-	0.618	100%

C&D Fines + CaO

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	402.82	80%	685	0.588	95%
CaO	100.70	20%	3350	0.030	5%
Total	503.52	100%	-	0.618	100%

C&D Fines + Ash 1

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	286.88	80%	685	0.419	68%
Ash 1	71.72	20%	360	0.199	32%
Total	358.60	100%	-	0.618	100%

C&D Fines + Zeolite

Item	Mass (g)	Mass (%)	Density (g/L)	Volume(L)	Volume %
C&D Fines	310.56	71%	685	0.454	73%
Zeolite	123.84	29%	754.8	0.164	27%
Total	434.40	100%	-	0.618	100%

Results

Column Data: Fines

Day	mL removed	mL added	otal mL adde	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	0.24	-	-	-	-	-	-
4	1	100	200	200	0.47	-	-	-	-	0.10	-
7	0	100	300	300	0.71	-	-	-	-	-	-
8	0	100	400	400	0.94	-	-	-	-	-	-
11	2	100	500	500	1.18	-	-	-	-	-	-
12	2	100	600	598	1.42	-	-	-	-	0.45	-
13	8	100	700	696	1.65	-	-	-	-	0.05	-
14	1	100	800	788	1.89	-	-	-	-	0.23	-
15	1	100	900	887	2.13	-	-	-	-	0.95	-
19	2	100	1000	986	2.36	-	-	-	-	-	0.000
20	1	100	1100	1084	2.60	-	-	-	-	-	-
21	1	100	1200	1183	2.83	-	-	-	-	-	-
22	2	100	1300	1282	3.07	-	-	-	-	-	-
25	0	100	1400	1380	3.31	-	-	-	-	0.00	0.022
26	35	100	1500	1480	3.54	-	-	-	-	0.00	-
27	63	100	1600	1545	3.78	-	-	-	-	0.14	-
28	68	100	1700	1582	4.01	6.66	-4.8	42	3.8	0.05	-
29	49	100	1800	1614	4.25	-	-	-	-	0.14	-
32	38	100	1900	1665	4.49	-	-	-	-	0.10	0
33	54	100	2000	1727	4.72	-	-	-	-	0.18	-
34	103	100	2100	1773	4.96	6.94	137	48.5	4.25	0.15	-
35	57	100	2200	1770	5.20	-	-	-	-	0.04	-
36	65	100	2300	1813	5.43	6.77	175	40.3	3.57	0.09	-
39	80	24	2400	1848	5.67	6.54	240	35.7	3.18	-	0
40	0	100	2424	1792	5.72	6.8	-14.9	32.2	2.89	-	-
41	0	24	2524	1892	5.96	-	-	-	-	-	-
42	0	0	2548	1916	6.02	-	-	-	-	-	-
43	91	100	2548	1916	6.02	-	-	-	-	-	-
46	0	0	2648	1925	6.25	6.67	-4.9	44.7	4	0.21	0
47	0	0	2648	1925	6.25	6.16	162	31.5	2.83	0.03	-
48	70	100	2648	1925	6.25	-	-	-	-	-	-
49	0	0	2748	1955	6.49	6.9	-89.6	31.3	2.78	0.30	-
50	0	0	2748	1955	6.49	-	-	-	-	-	-
57	0	0	2748	1955	6.49	-	-	-	-	-	0
60	68	100	2748	1955	6.49	0	0	0	0	0.00	0
64	0	0	2848	1987	6.73	6.99	-147.6	28.4	2.6	0.30	
67	80	100	2848	2007	6.73	-	-	-	-	-	0.054
71	0	0	2948	2007	6.96	7.54	-128	25	2.21	0.40	
74	70	100	2948	2037	6.96	-	-	-	-	-	0.015
78	0	0	3048	2037	7.20	7.11	-117.1	38	3.3	0.20	-
81	77	100	3048	2060	7.20	-	-	-	-	-	0.002
85	0	0	3148	2060	7.43	6.91	-102	40.1	3.45	0.08	-
89	68	100	3148	2092	7.43	-	-	-	-	-	0.11
92	0	0	3248	2092	7.67	6.9	-88.2	42	3.6	0.10	-
95	70	100	3248	2122	7.67	-	-	-	-	-	0
99	0	0	3348	2122	7.91	6.88	-111	24.6	2.1	0.08	-
102	82	100	3448	2140	8.14	-	-	-	-	-	0.001
109	105	100	3548	2135	8.38	6.91	-110.1	36.1	3.08	0.18	-
113	0	0	3548	2135	8.38	10.26	-233	44.4	3.8	0.15	-
117	75	100	3648	2160	8.62	6.9	-80.1	33	2.78	0.00	-
120	0	0	3648	2160	8.62	-	-	-	-	-	1.4
123	70	100	3748	2190	8.85	6.9	-91	36.7	3.1	-	-
127	0	0	3748	2190	8.85	-	-	-	-	-	0.67
130	80	100	3848	2210	9.09	7.2	-49	45	3.79	0.15	-
134	0	0	3848	2210	9.09	-	-	-	-	-	0.38
137	75	100	3948	2235	9.32	7.13	-80	50	4.02	0.33	-
141	0	0	3948	2235	9.32	-	-	-	-	-	2.7
144	92	100	4048	2243	9.56	7.12	-110	39.6	3.22	0.33	-
148	0	0	4048	2243	9.56	-	-	-	-	-	0.93
151	89	100	4148	2254	9.80	7.07	-151	33.8	2.82	0.28	-
155	0	0	4148	2254	9.80	-	-	-	-	-	1.8
158	105	100	4248	2249	10.03	7.46	-227	20.8	1.68	1.03	-
162	0	0	4248	2249	10.03	-	-	-	-	-	0.24

Column Data: Fines + Lime_1

Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	0.20	-	-	-	-	-	-
4	0	100	200	200	0.41	-	-	-	-	-	-
6	7	100	300	293	0.61	-	-	-	-	0.11	-
7	66	100	400	327	0.81	12.09	-58.7	44	4.01	0.13	-
8	86	100	500	341	1.02	12.19	-174.3	31.1	2.69	0.08	-
11	85	100	600	356	1.22	12.31	-159	36.4	3.16	0.11	-
12	78	100	700	378	1.43	12.27	-96.8	41.2	3.63	0.06	-
13	89	100	800	389	1.63	12.22	-127.8	37.8	3.3	0.11	-
14	48	100	900	441	1.83	12	-35	55	5	0.04	-
15	70	100	1000	471	2.04	12	-108	36	3	-	0.000
19	65	100	1100	506	2.24	12.22	31	32.6	2.87	-	-
20	88	100	1200	518	2.44	12.17	29	35.8	3.18	0.10	-
21	90	100	1300	528	2.65	12.16	63.2	42.8	3.8	0.01	-
22	0	24	1324	552	2.70	-	-	-	-	-	0.001
25	0	24	1348	576	2.74	-	-	-	-	-	-
26	0	24	1372	600	2.79	-	-	-	-	-	-
27	0	24	1396	624	2.84	-	-	-	-	-	-
28	80	24	1420	568	2.89	12.03	4	33.3	2.97	0.04	-
29	0	24	1444	592	2.94	-	-	-	-	-	0.004
32	0	24	1468	616	2.99	-	-	-	-	-	-
33	0	24	1492	640	3.04	-	-	-	-	-	-
34	0	24	1516	664	3.09	-	-	-	-	-	-
35	95	24	1540	593	3.14	11.97	7	34.7	3.03	0.04	-
36	0	24	1564	617	3.18	-	-	-	-	-	0.008
39	0	24	1588	641	3.23	-	-	-	-	-	-
40	0	24	1612	665	3.28	-	-	-	-	-	-
41	0	24	1636	689	3.33	-	-	-	-	-	-
42	0	100	1736	789	3.53	-	-	-	-	-	-
43	0	0	1736	789	3.53	-	-	-	-	-	0.002
46	0	0	1736	789	3.53	-	-	-	-	-	-
47	0	100	1836	889	3.74	-	-	-	-	-	-
48	0	0	1836	889	3.74	-	-	-	-	-	-
49	0	0	1836	889	3.74	-	-	-	-	-	-
50	67	100	1936	922	3.94	12.2	66.3	43.4	3.72	0.04	0
57	0	100	2036	1022	4.14	-	-	-	-	-	-
60	5	100	2136	1117	4.35	-	-	-	-	-	
64	0	0	2136	1117	4.35	-	-	-	-	-	0.137
67	81	100	2236	1136	4.55	12.79	-169	39	3.3	0.03	
71	0	0	2236	1136	4.55	-	-	-	-	-	0.011
74	0	100	2336	1236	4.76	-	-	-	-	-	0
78	0	0	2336	1236	4.76	-	-	-	-	-	-
81	70	100	2436	1266	4.96	12.05	-162	74.6	6.29	0.10	-
85	0	0	2436	1266	4.96	-	-	-	-	-	-
89	65	100	2536	1301	5.16	12.05	-155.9	77	6	1.83	0
92	0	0	2536	1301	5.16	-	-	-	-	-	-
95	5	100	2636	1396	5.37	-	-	-	-	0.08	0
99	0	0	2636	1396	5.37	-	-	-	-	-	0.001
102	5	100	2736	1491	5.57	-	-	-	-	2.08	0
109	97	100	2836	1494	5.77	10.64	-225.5	45.3	3.88	0.05	
113	0	0	2836	1494	5.77	-	-	-	-	-	0.65
117	90	100	2936	1504	5.98	12.05	-174.6	52.9	4.43	0.03	0
123	88	100	3036	1516	6.18	12.05	-169	60.8	5.1	-	-
127	0	0	3036	1516	6.18	-	-	-	-	-	0.38
130	90	100	3136	1526	6.38	12.13	-85	44	3.65	0.25	-
134	0	0	3136	1526	6.38	-	-	-	-	-	-
137	90	100	3236	1536	6.59	12.01	-108	54	4.4	0.00	-
141	0	0	3236	1536	6.59	-	-	-	-	-	3
144	85	100	3336	1551	6.79	11.99	-208.1	34.1	2.74	0.20	-
148	0	0	3336	1551	6.79	-	-	-	-	-	1.9
151	80	100	3436	1571	6.99	11.9	-185	39.1	3.24	1.95	-
155	0	0	3436	1571	6.99	-	-	-	-	-	3.7
158	95	100	3536	1576	7.20	12.55	-250	44.6	3.66	0.00	-
162	0	0	3536	1576	7.20	-	-	-	-	-	0.34

Column Data: Fines + Lime_2

Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	0.20	-	-	-	-	-	-
4	0	100	200	200	0.41	-	-	-	-	-	-
6	0	100	300	300	0.61	-	-	-	-	-	-
7	7	100	400	393	0.81	-	-	-	-	0.06	-
8	0	100	500	493	1.02	-	-	-	-	-	-
11	56	100	600	537	1.22	12.35	-141.3	49	4.26	0.03	-
12	76	100	700	561	1.43	12.33	-100.7	52.9	4.67	0.04	-
13	77	100	800	584	1.63	12.32	-117.2	50.2	4.35	0.03	-
14	78	100	900	606	1.83	12	-53	46	4	0.03	-
15	81	100	1000	625	2.04	12	-99	43	4	-	0.002
19	70	100	1100	655	2.24	12.38	-9	31.9	2.74	-	
20	79	100	1200	676	2.44	12.25	18.2	43.9	3.92	0.14	
21	80	100	1300	696	2.65	12.23	50	44	3.88	0.05	
22	0	24	1324	720	2.70	-	-	-	-	-	0.000
25	0	24	1348	744	2.74	-	-	-	-	-	-
26	0	24	1372	768	2.79	-	-	-	-	-	-
27	0	24	1396	792	2.84	-	-	-	-	-	-
28	86	24	1420	730	2.89	12.15	-29.5	32.2	2.86	0.01	-
29	0	24	1444	754	2.94	-	-	-	-	-	0.004
32	0	24	1468	778	2.99	-	-	-	-	-	-
33	0	24	1492	802	3.04	-	-	-	-	-	-
34	0	24	1516	826	3.09	-	-	-	-	-	-
35	78	24	1540	772	3.14	12.01	-19.9	35.9	3.14	0.04	-
36	0	24	1564	796	3.18	-	-	-	-	-	0.011
39	0	24	1588	820	3.23	-	-	-	-	-	-
40	0	24	1612	844	3.28	-	-	-	-	-	-
41	0	24	1636	868	3.33	-	-	-	-	-	-
42	0	100	1736	968	3.53	-	-	-	-	-	-
43	0	0	1736	968	3.53	-	-	-	-	-	0
46	0	0	1736	968	3.53	-	-	-	-	-	-
47	65	100	1836	1003	3.74	12.32	47.5	43.5	3.74	0.09	-
48	0	0	1836	1003	3.74	-	-	-	-	-	-
49	0	0	1836	1003	3.74	-	-	-	-	-	-
50	67	100	1936	1036	3.94	12.32	51.5	40	3.44	0.01	0
57	0	100	2036	1136	4.14	-	-	-	-	-	0.018
60	65	100	2136	1171	4.35	11.93	-141	46	4.04	0.00	
64	0	0	2136	1171	4.35	-	-	-	-	-	0.002
67	80	100	2236	1191	4.55	12.75	-194	43	3.64	0.09	
71	0	0	2236	1191	4.55	-	-	-	-	-	0.011
74	68	100	2336	1223	4.76	12.23	-180.3	66.7	5.59	0.00	0
78	0	0	2336	1223	4.76	-	-	-	-	-	0
81	75	100	2436	1248	4.96	12.15	-154.7	66.1	5.46	0.13	-
85	0	0	2436	1248	4.96	-	-	-	-	-	0.18
89	72	100	2536	1276	5.16	12.14	-151	66	5.7	0.00	-
92	0	0	2536	1276	5.16	-	-	-	-	-	0
95	76	100	2636	1300	5.37	11.76	-171.4	47.1	3.97	0.08	-
99	0	0	2636	1300	5.37	-	-	-	-	-	0.002
102	87	100	2736	1313	5.57	12.08	-178	47.5	3.89	0.50	-
109	83	100	2836	1330	5.77	10.28	-209.1	61.4	5.1	0.10	-
113	0	0	2836	1330	5.77	-	-	-	-	-	0.16
117	73	100	2936	1357	5.98	12.09	-150	50	4.26	0.10	-
120	0	0	2936	1357	5.98	-	-	-	-	-	0
123	77	100	3036	1380	6.18	12.1	-133	57.8	4.86	0.00	-
127	0	0	3036	1380	6.18	-	-	-	-	-	0.26
130	72	100	3136	1408	6.38	12.15	-50.8	45.8	3.8	0.20	-
134	0	0	3136	1408	6.38	-	-	-	-	-	0.16
137	75	100	3236	1433	6.59	12.02	-70	45	3.7	0.13	-
141	0	0	3236	1433	6.59	-	-	-	-	-	13
144	80	100	3336	1453	6.79	11.98	-144	41.2	3.4	0.18	-
148	0	0	3336	1453	6.79	-	-	-	-	-	3.1
151	80	100	3436	1473	6.99	11.9	-150	43.3	3.58	0.65	-
155	0	0	3436	1473	6.99	-	-	-	-	-	4.1
158	80	100	3536	1493	7.20	12.59	-208	49.8	4.1	0.00	-
162	0	0	3536	1493	7.20	-	-	-	-	-	1.3

Column Data: Fines + Quicklime

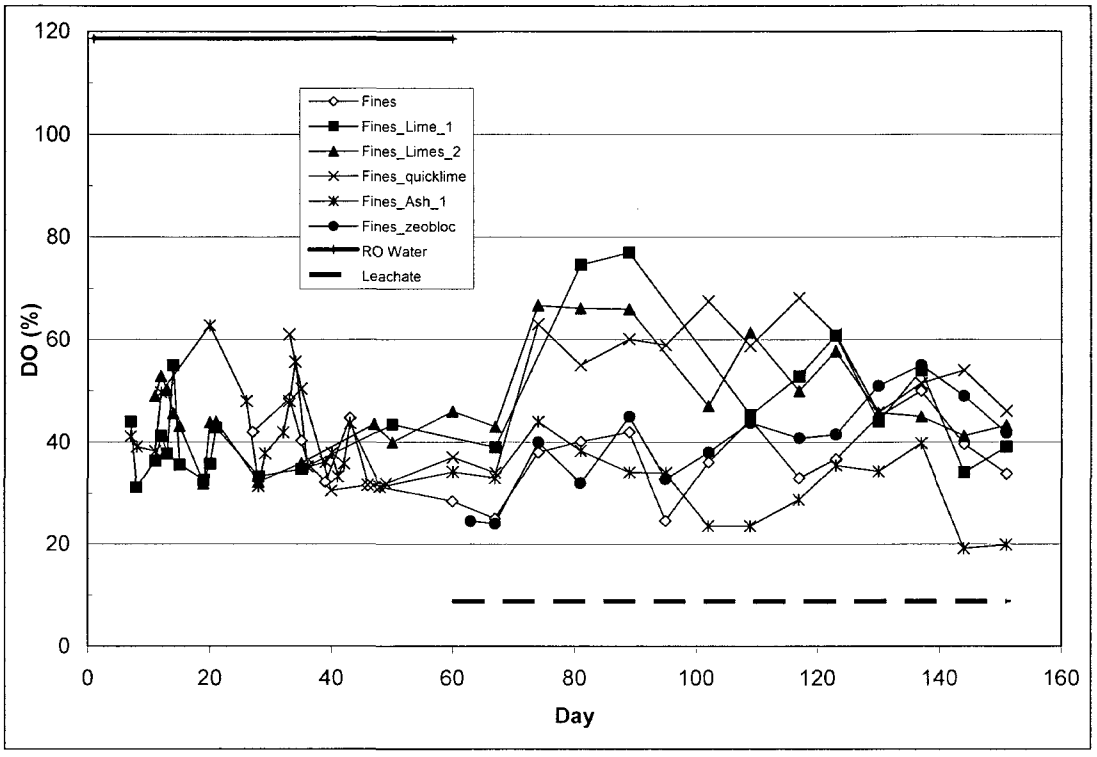
Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	0.20	-	-	-	-	-	-
4	0	100	200	200	0.40	-	-	-	-	-	-
6	0	100	300	300	0.60	-	-	-	-	-	-
7	0	100	400	400	0.79	-	-	-	-	-	-
8	0	100	500	500	0.99	-	-	-	-	-	-
11	23	100	600	577	1.19	-	-	-	-	0.03	-
12	11	100	700	666	1.39	-	-	-	-	0.04	-
13	26	100	800	740	1.59	-	-	-	-	0.03	-
14	26	100	900	814	1.79	-	-	-	-	0.05	-
15	30	100	1000	884	1.99	-	-	-	-	-	0.007
19	21	100	1100	963	2.18	-	-	-	-	-	
20	30	100	1200	1033	2.38	-	-	-	-	0.00	
21	29	100	1300	1104	2.58	-	-	-	-	0.01	
22	3	100	1400	1201	2.78	-	-	-	-	0.00	0.000
25	1	100	1500	1300	2.98	-	-	-	-	0.03	-
26	17	100	1600	1383	3.18	-	-	-	-	0.00	-
27	55	100	1700	1428	3.38	-	-	-	-	0.01	-
28	34	100	1800	1494	3.57	-	-	-	-	0.00	-
29	56	100	1900	1538	3.77	-	-	-	-	0.05	0.003
32	25	100	2000	1613	3.97	-	-	-	-	0.08	-
33	63	100	2100	1650	4.17	12.11	-79.3	61	5.45	0.09	-
34	68	100	2200	1682	4.37	-	-	-	-	0.00	-
35	66	100	2300	1716	4.57	12.08	-57.9	50.4	4.39	0.03	-
36	30	100	2400	1786	4.77	-	-	-	-	-	0.009
39	37	100	2500	1849	4.97	-	-	-	-	-	-
40	91	100	2600	1858	5.16	11.05	-121.9	30.5	2.69	-	-
41	0	0	2600	1858	5.16	-	-	-	-	-	-
42	0	0	2600	1858	5.16	-	-	-	-	-	-
43	0	0	2600	1858	5.16	-	-	-	-	-	-
46	89	100	2700	1869	5.36	11.76	-124.5	31.6	2.76	0.05	-
47	0	0	2700	1869	5.36	-	-	-	-	-	-
48	0	0	2700	1869	5.36	-	-	-	-	-	-
49	60	100	2800	1909	5.56	12.39	-115.5	31.9	2.74	0.03	-
50	0	0	2800	1909	5.56	-	-	-	-	-	0
57	0	0	2800	1909	5.56	0	0	0	0	0.00	0.002
60	60	100	2900	1949	5.76	12.02	-148.5	37	3.05	0.08	-
64	0	0	2900	1949	5.76	-	-	-	-	-	0
67	63	100	3000	1986	5.96	12.8	-188	34	2.9	0.03	-
71	0	0	3000	1986	5.96	-	-	-	-	-	0.002
74	60	100	3100	2026	6.16	12.31	-172	63	5.25	0.00	0
78	0	0	3100	2026	6.16	-	-	-	-	-	0
81	68	100	3200	2058	6.36	12.19	-151.5	55	4.67	0.18	-
85	0	0	3200	2058	6.36	-	-	-	-	-	0.14
89	70	100	3300	2088	6.55	12.13	-145.8	60.1	5.1	0.00	-
92	0	0	3300	2088	6.55	-	-	-	-	-	0
95	72	100	3400	2116	6.75	11.88	-155.4	59	4.9	0.10	-
99	0	0	3400	2116	6.75	-	-	-	-	-	0.003
102	75	100	3500	2141	6.95	12.15	-161	67.5	5.6	0.15	0
109	100	100	3600	2141	7.15	9.95	-193.3	58.8	4.95	0.15	
113	0	0	3600	2141	7.15	-	-	-	-	-	0.01
117	75	100	3700	2166	7.35	12.12	-139.5	68.2	5.7	0.00	-
123	91	100	3800	2175	7.55	12.12	-104.5	61.1	5.13	0.00	-
127	0	0	3800	2175	7.55	-	-	-	-	-	0.2
130	70	100	3900	2205	7.75	12.2	-41	45.8	3.75	0.08	-
134	0	0	3900	2205	7.75	-	-	-	-	-	0.13
137	70	100	4000	2235	7.94	12.06	-65	51.5	4.23	0.10	-
141	0	0	4000	2235	7.94	-	-	-	-	-	-
144	78	100	4100	2257	8.14	12.03	-124	54	4.38	0.13	-
148	0	0	4100	2257	8.14	-	-	-	-	-	3.3
151	75	100	4200	2282	8.34	11.97	-131.6	46.1	3.79	0.55	-
155	0	0	4200	2282	8.34	-	-	-	-	-	4.7
158	80	100	4300	2302	8.54	12.65	-199	52.5	4.29	0.00	-
162	0	0	4300	2302	8.54	-	-	-	-	-	3.5

Column Data: Fines + Ash_1

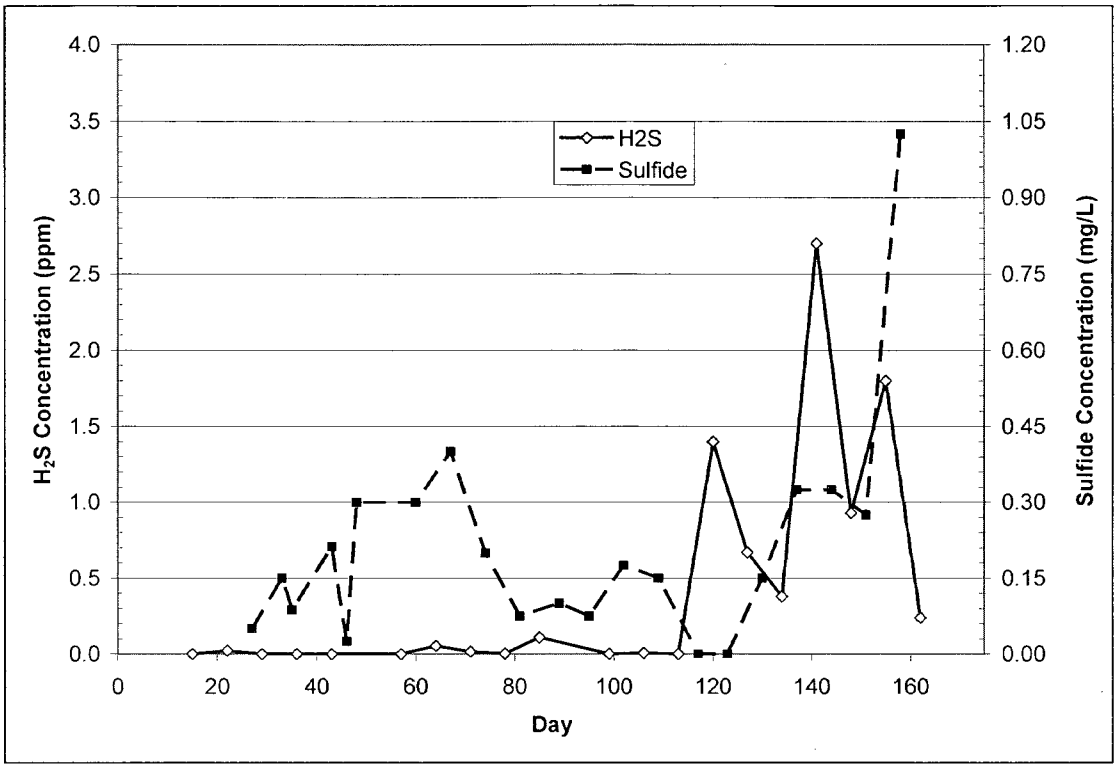
Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
1	0	100	100	100	0.28	-	-	-	-	-	-
4	0	100	200	200	0.56	-	-	-	-	-	-
6	25	100	300	275	0.84	-	-	-	-	0.16	-
7	64	100	400	311	1.12	7.38	81	41.1	3.43	0.63	-
8	80	100	500	331	1.39	7.42	-23.5	39.1	3.4	0.36	-
11	72	100	600	359	1.67	7.94	-79	38.2	3.35	0.23	-
12	48	100	700	411	1.95	8.15	-31.3	49.7	4.46	0.06	-
13	0	100	800	511	2.23	-	-	-	-	-	-
14	6	100	900	605	2.51	-	-	-	-	0.04	-
15	14	100	1000	691	2.79	-	-	-	-	-	0.007
19	0	100	1100	791	3.07	-	-	-	-	-	-
20	42	100	1200	849	3.35	7.29	177	62.8	5.84	0.08	-
21	19	100	1300	930	3.63	-	-	-	-	0.00	-
22	3	100	1400	1027	3.90	-	-	-	-	0.00	0.000
25	3	100	1500	1124	4.18	-	-	-	-	0.04	-
26	63	100	1600	1161	4.46	6.92	62	48	4.35	0.05	-
27	0	100	1700	1261	4.74	-	-	-	-	-	-
28	65	100	1800	1296	5.02	8.51	16	31.4	2.77	0.00	-
29	61	100	1900	1335	5.30	6.82	165	37.8	3.42	0.09	0.014
32	63	100	2000	1372	5.58	6.69	25.8	41.9	3.72	0.10	-
33	70	100	2100	1402	5.86	8.65	7.7	48	4.29	0.06	-
34	80	100	2200	1422	6.14	6.94	131.3	55.7	4.93	0.05	-
35	78	100	2300	1444	6.41	-	-	-	-	-	-
36	70	100	2400	1474	6.69	6.82	124	35.2	3.14	-	0.014
39	72	100	2500	1502	6.97	6.8	-64.5	36.1	3.59	-	-
40	60	100	2600	1542	7.25	6.77	-45.5	37.9	3.39	-	-
41	67	100	2700	1575	7.53	6.79	-57	33.3	2.95	-	-
42	80	100	2800	1595	7.81	6.8	-13	35.8	3.2	0.00	-
43	70	100	2900	1625	8.09	6.8	-45.5	43.7	3.89	0.00	0
46	0	0	2900	1625	8.09	-	-	-	-	-	-
47	0	0	2900	1625	8.09	-	-	-	-	-	-
48	63	100	3000	1662	8.37	6.9	-88	31.2	2.78	0.18	-
49	0	0	3000	1662	8.37	-	-	-	-	-	-
50	0	0	3000	1662	8.37	-	-	-	-	-	0
57	0	0	3000	1662	8.37	-	-	-	-	-	0
60	70	100	3100	1692	8.64	6.99	-131.4	34.2	3.04	0.18	
64	0	0	3100	1692	8.64	-	-	-	-	-	0
67	81	100	3200	1711	8.92	7.53	-116.1	33	2.88	0.23	
71	0	0	3200	1711	8.92	-	-	-	-	-	0.002
74	71	100	3300	1740	9.20	7.24	-128.6	44	3.7	0.25	0
78	0	0	3300	1740	9.20	-	-	-	-	-	0.004
81	86	100	3400	1754	9.48	6.94	-118.2	38.3	3.21	0.00	-
85	0	0	3400	1754	9.48	-	-	-	-	-	-
89	80	100	3500	1774	9.76	7.02	-94.2	34.1	2.94	0.03	0
92	0	0	3500	1774	9.76	-	-	-	-	-	0
95	100	100	3600	1774	10.04	7.2	-93.8	34	2.89	0.00	0
99	0	0	3600	1774	10.04	-	-	-	-	-	0.5
102	81	100	3700	1793	10.32	7.2	-98.1	23.6	2.05	0.43	-
109	110	100	3800	1783	10.60	8.49	-169	23.6	2	0.05	-
113	0	0	3800	1783	10.60	-	-	-	-	-	0.001
117	100	100	3900	1783	10.88	7.1	-60	28.7	2.42	0.20	-
120	0	0	3900	1783	10.88	-	-	-	-	-	0.014
123	93	100	4000	1790	11.15	7.11	-77.5	35.5	2.98	0.08	-
127	0	0	4000	1790	11.15	-	-	-	-	-	1.2
130	94	100	4100	1796	11.43	7.26	-122.5	34.3	2.84	-	-
134	0	0	4100	1796	11.43	-	-	-	-	0.00	0.18
137	110	100	4200	1786	11.71	7.15	-113	39.8	3.41	0.23	-
141	0	0	4200	1786	11.71	-	-	-	-	-	0.11
144	99	100	4300	1787	11.99	7.16	-128.5	19.2	1.51	0.28	-
148	0	0	4300	1787	11.99	-	-	-	-	-	1.7
151	100	100	4400	1787	12.27	7.12	-172	19.9	1.64	0.35	-
155	0	0	4400	1787	12.27	-	-	-	-	-	1.7
158	100	100	4500	1787	12.55	7.52	-193	12.2	1.01	0.00	-
162	0	0	4500	1787	12.55	-	-	-	-	-	1.8

Column Data: Fines + ZeoBloc ™

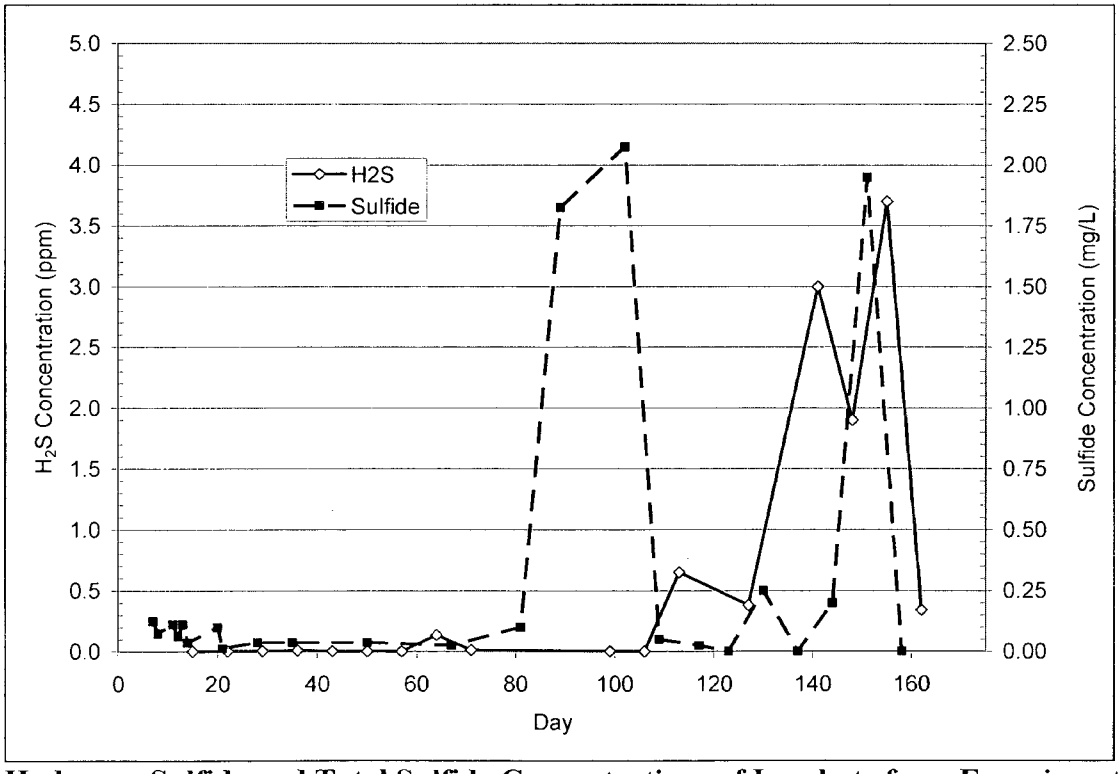
Day	mL removed	mL added	total mL added	total mL	LSR (mL/g)	pH	ORP (mV)	DO (%)	DO (mg/L)	Sulfides (mg/L)	H_2S Conc (ppm)
60	0	100	100	100	0.23	-	-	-	-	-	-
61	0	100	200	200	0.46	-	-	-	-	-	-
62	35	100	300	265	0.69	-	-	-	-	0.31	-
63	75	100	400	290	0.92	6.74	86.3	24.5	2.11	0.66	0
64	0	0	400	-	0.92	-	-	-	-	-	0.001
67	70	100	500	320	1.15	7.46	-99	24	2.03	0.35	-
71	0	0	500	-	1.15	-	-	-	-	-	0.003
74	80	100	600	340	1.38	7.07	-65	40	3.3	0.55	-
78	0	0	600	-	1.38	-	-	-	-	-	0.001
81	98	100	700	342	1.61	6.91	-93	32	2.68	0.60	-
85	0	0	700	-	1.61	-	-	-	-	-	0
89	90	100	800	352	1.84	6.94	-46.1	45	3.83	0.08	-
92	0	0	800	-	1.84	-	-	-	-	-	0
95	91	100	900	361	2.07	6.88	-74.5	32.8	2.77	0.13	-
99	0	0	900	-	2.07	-	-	-	-	-	0.53
102	91	100	1000	370	2.30	6.93	-51.2	38	3.22	0.00	-
109	85	100	1100	385	2.53	6.92	-60.2	43.8	3.75	0.18	-
113	0	0	1100	0	2.53	-	-	-	-	-	0.24
117	87	100	1200	398	2.76	6.83	-90.5	40.8	4.43	0.00	-
120	0	0	1200	0	2.76	-	-	-	-	-	0.13
123	73	100	1300	425	2.99	6.84	-68	41.5	3.46	0.18	-
127	0	0	1300	0	2.99	-	-	-	-	-	0.88
130	70	100	1400	455	3.22	7.03	-93	51	4.2	-	-
134	0	0	1400	0	3.22	-	-	-	-	-	0.42
137	65	100	1500	490	3.45	6.96	-133	55	4.55	0.15	-
141	0	0	1500	0	3.45	-	-	-	-	-	2.3
144	93	100	1600	497	3.68	7.06	-103	49	4.04	0.18	-
148	0	0	1600	0	3.68	-	-	-	-	-	0.21
151	80	100	1700	517	3.91	6.99	-88	41.8	3.54	0.15	-
155	0	0	1700	0	3.91	-	-	-	-	-	0.27
158	87	100	1800	530	4.14	7.42	-80	41	3.45	0.00	-
162	0	0	1800	0	4.14	-	-	-	-	-	0.37



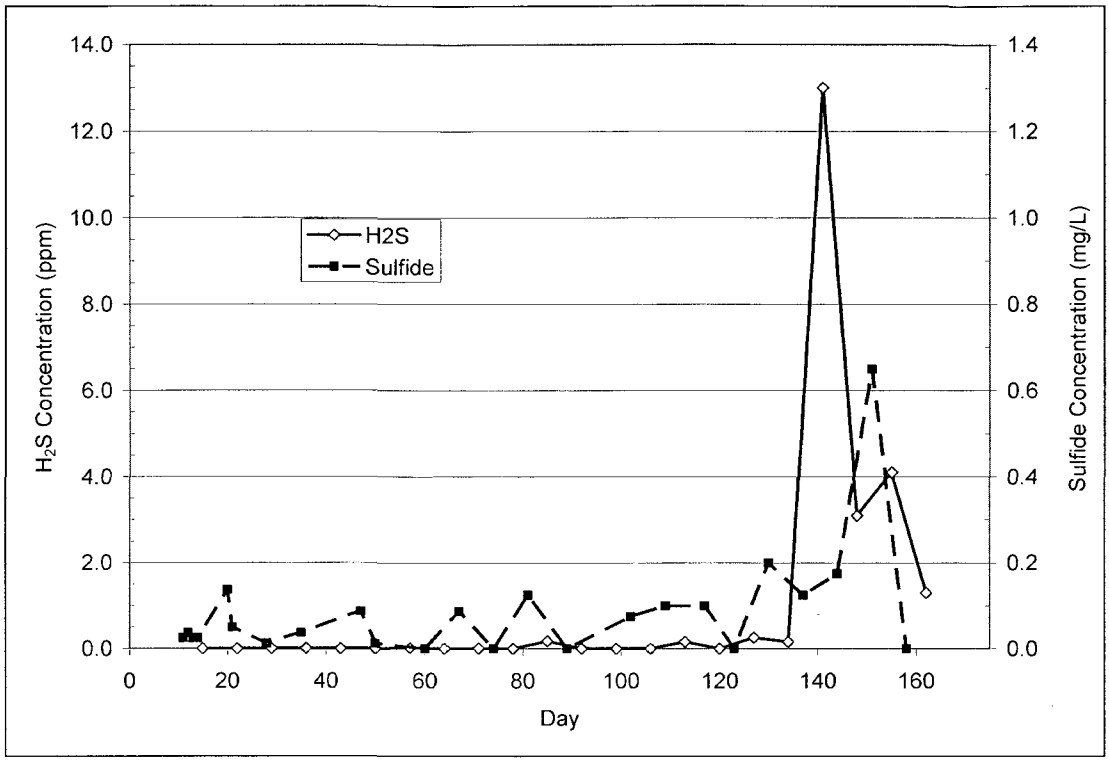
Dissolved Oxygen Concentrations of Leachate from Experimental Columns



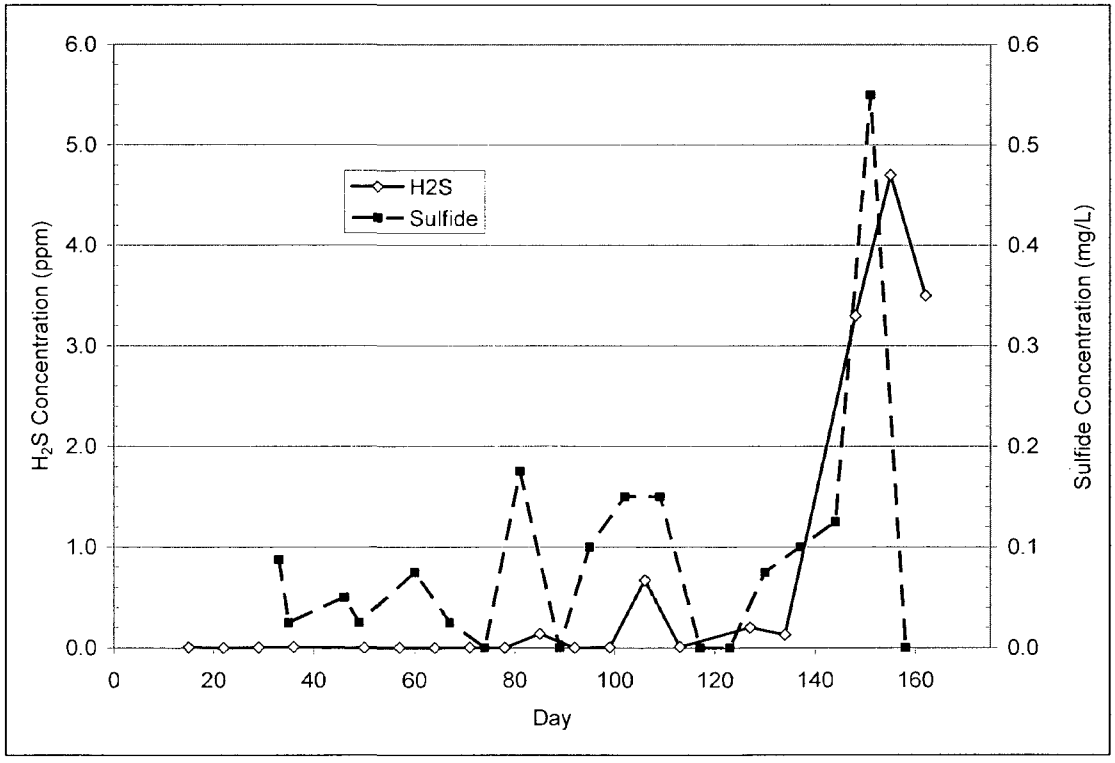
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines



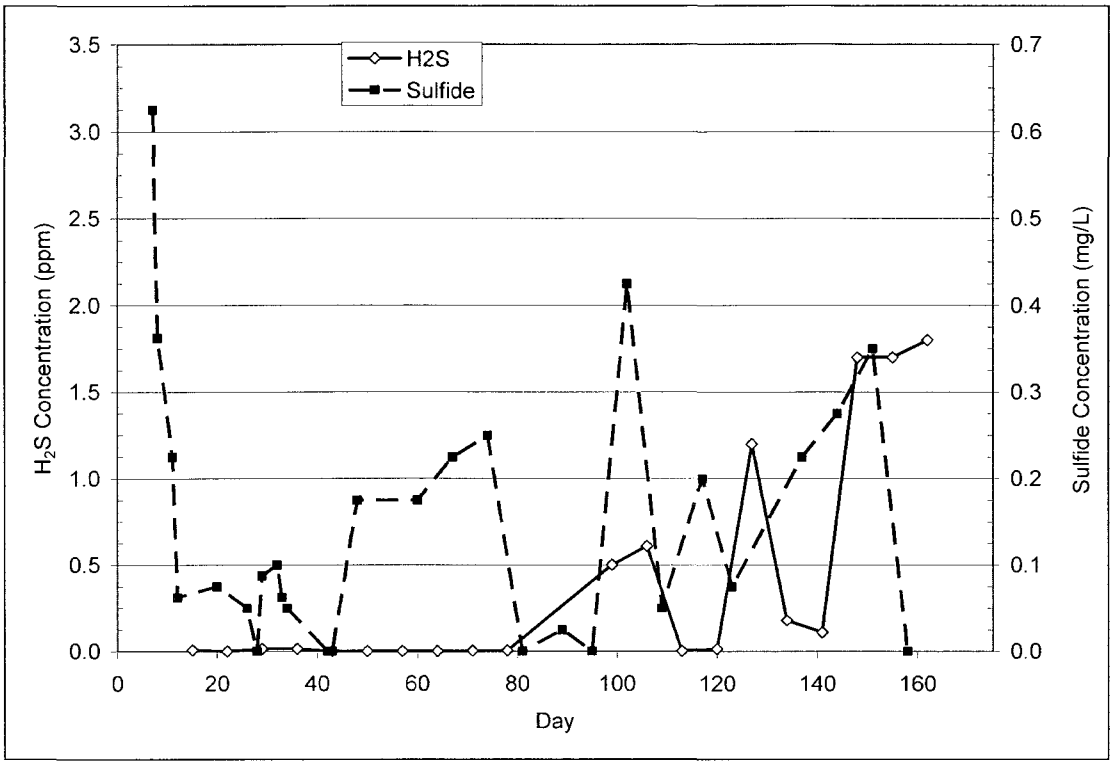
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines and Lime-1



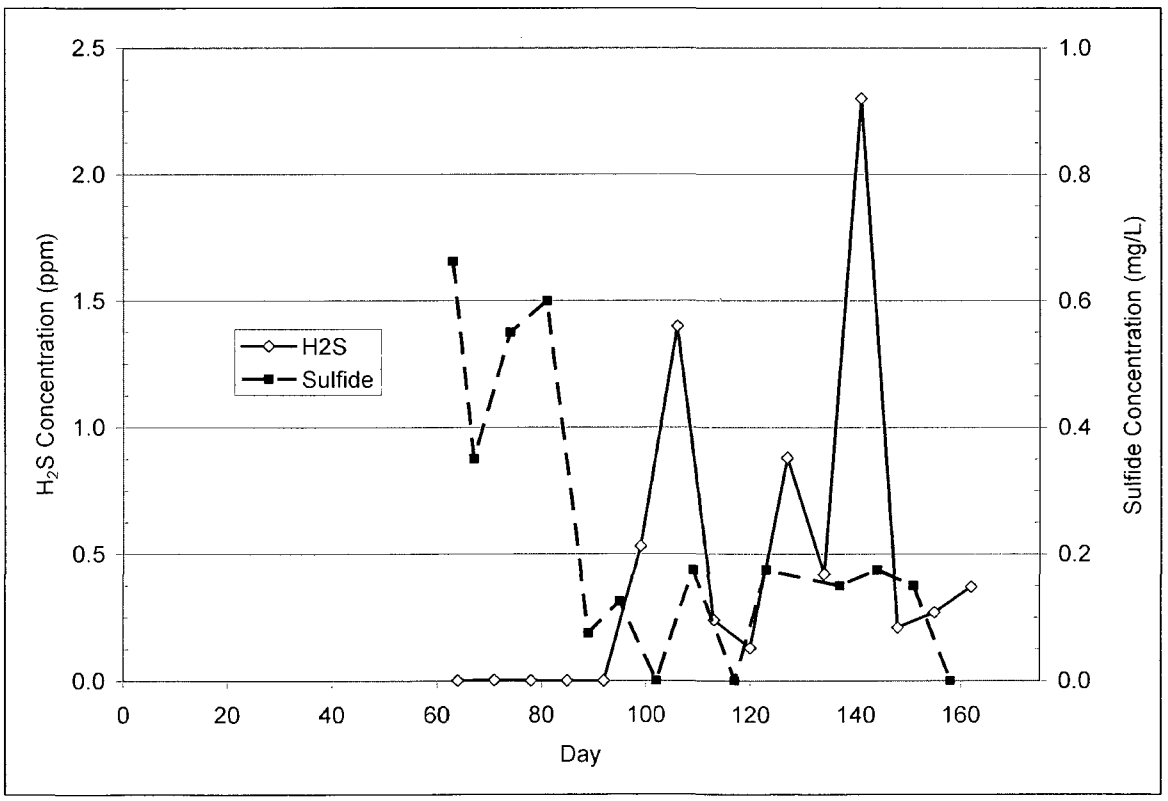
Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines and Lime-2



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines and Quicklime



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines and Ash-1



Hydrogen Sulfide and Total Sulfide Concentrations of Leachate from Experimental Column: Fines and Zeobloc Powder

APPENDIX E

Instrument Precision and Accuracy

JEROME® Hydrogen Sulfide Analyzer – Arizona Instruments

Concentration	Accuracy
0.001 to 0.099 ppm	+/-0.003ppm
0.10 to 0.99 ppm	+/-0.03ppm
1.0 to 9.9 ppm	+/-0.3ppm
10 to 50 ppm	+/-2ppm

Gas Detection Tubes - RAE Systems

Range	Precision
2.5-60 ppmv	+/- 12% Reading
50-800 ppmv	+/- 10% Reading
0.1 - 2%	+/- 10% Reading

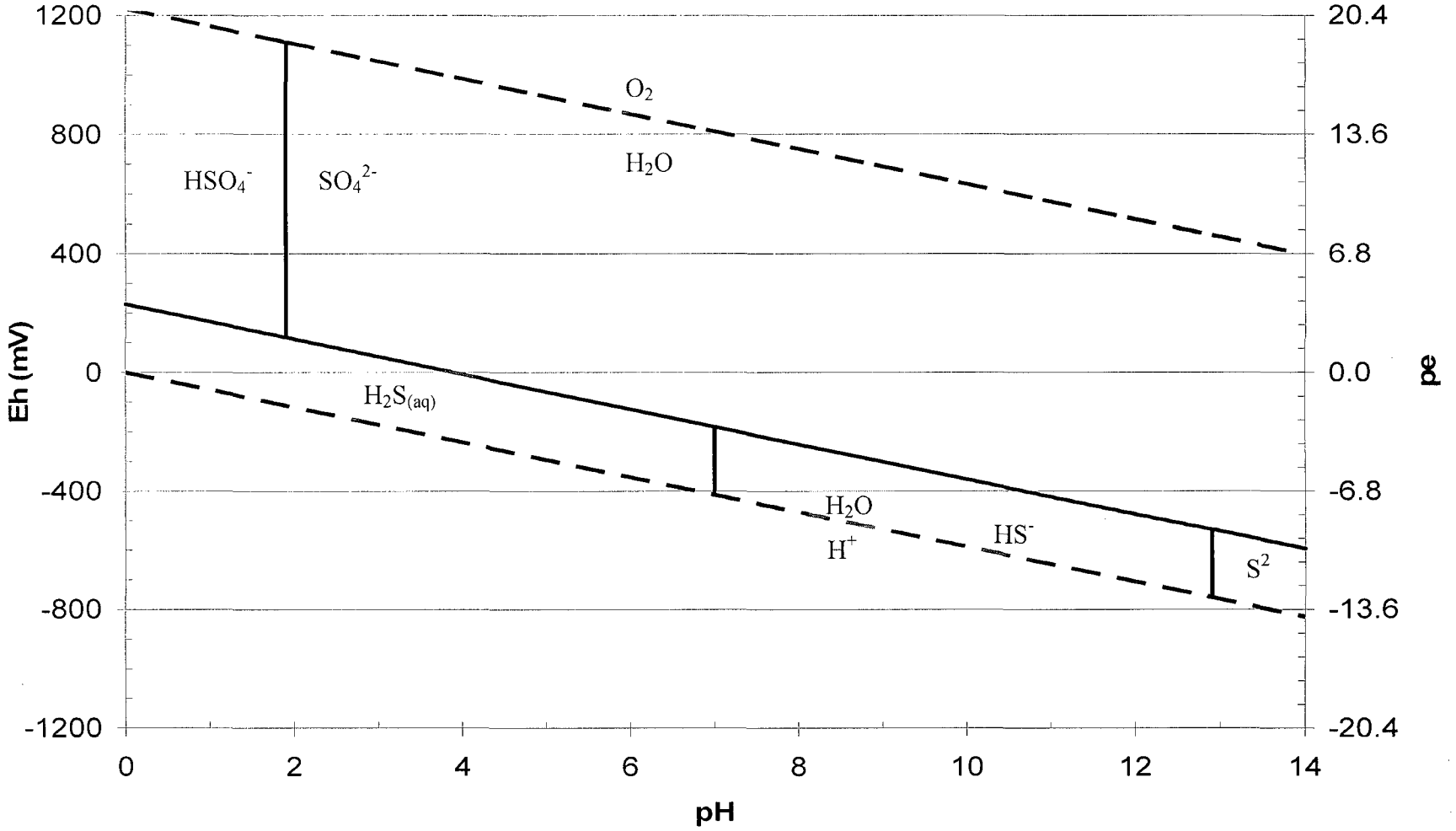
YSI556 Multi Probe System

Parameter	Range	Precision
Dissolved Oxygen (% Saturation)	0 - 500% Air Saturation	+/- 2% Air Saturation
Dissolved Oxygen (mg/L)	0 - 50 mg/L	+/- 2 mg/L
pH	0 - 14 pH units	+/- 0.2 pH units
Oxidation Reduction Potential	-999 - +999 mV	+/- 20 mV

DR/2000 Spectrophotometer – HACH
Method 8131 (sulfide)
Accuracy +/- 2%

APPENDIX F

Oxidation Reduction Potential/pH Diagram for the Sulfur System



Eh and pe Diagram vs pH for the Sulfur System